Comprehensive Planning Study of Maintenance Facilities for the Connecticut Department of Transportation

Final Report

December 31, 1991

JHR 91-206 Project 90-6

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16. Abstract

This study was prompted by a recommendation of the Commission to Study the Management of State Government, also known as the Thomas Commission. The recommendation stated that savings might be realized through the consolidation of the Connecticut Department of Transportation's thirteen equipment repair facilities. In this study, an optimization model is developed to represent the problem of reconfiguring the repair system to minimize total costs while maintaining the existing level of service.

Based on runs of the optimization model, two recommended options are developed. One option closes three repair facilities for an estimated savings of $ 5.01 million, and the other option closes two facilities for a savings of $ 3.12 million. An advantage of the eleven facility option is that it does not require any new construction prior to implementation. This report presents details of the recommended options, and completely describes the analysis and assumptions upon which the recommendations are based.

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Finally, we acknowledge the assistance of Brett Stoefler, a Civil Engineering Graduate Assistant at UConn who provided considerable assistance in accumulating equipment counts and calculating travel distances for the model used in this study.

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
in	inches	25.4	millimetres	mm
ft	feet	0.305	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
	AREA			
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.093	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometres squared	km^2
	VOLUME			
fl oz	fluid ounces	29.57	mililitres	mL
gal	gallons	3.785	Litres	L
ft^3	cubic feet	0.028	metres cubed	m^3
yd^3	cubic yards	0.765	metres cubed	m^3

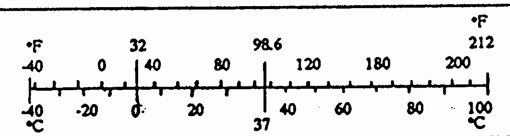
NOTE: Volumes greator than 1000 L shall be shown in m^3.

Symbol	When You Know	Multiply By	To Find	Symbol
	MASS			
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5(F-32)/9	Celcius temperature	°C

*SI is the symbol for the International System of Measurement

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
	AREA			
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
ha	hectares	2.47	acres	ac
km^2	kilometres squared	0.386	square miles	mi^2
	VOLUME			
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3
	MASS			
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
	TEMPERATURE (exact)			
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F



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I. INTRODUCTION

Background

This study is concerned with the system that services the equipment used to maintain Connecticut's roadways. The equipment is currently serviced at thirteen repair facilities located around the State, plus one machine shop in Portland. The study investigates the possibility of serving the equipment at reduced costs by operating with fewer than thirteen repair facilities.

The impetus for this study came as a result of work done by the Commission to Study the Management of State Government, also known as the Thomas Commission. Recommendation IV.5 of the Thomas Commission report states that a study should be undertaken to "address projected maintenance capacity needs and the issue of upgrading and consolidating existing facilities." The report further states that "the need for all of the existing facilities is not apparent," and it suggests that consolidation of some facilities might "result in a more productive use of equipment and manpower and provide ConnDOT with revenue from the sale of quite valuable property in some cases."

Figure 1 presents a diagram that represents the State's existing equipment repair system. The circles and triangles in this figure depict the locations of maintenance garages and other buildings where significant quantities of equipment are housed. The towns, building numbers, and functions of these locations are listed in Table B.2 in Appendix B. Whenever equipment requires maintenance, it is transported from these locations to the repair facilities, which are represented by the squares in Figure 1. Each straight line in Figure 1 indicates an existing assignment of a garage to a repair facility. With few exceptions, all equipment from a garage goes to the same facility for repair, and all facilities are capable of performing all types of repairs. For this study, the major repairs performed only at the Portland machine shop are not included, since the possibility of closing that facility is not being considered here as an option.

There is a wide variety of equipment housed at the garages represented in Figure 1. For this study, we have categorized the dozens of different types of equipment based on similarities of maintenance requirements. Overall, there are approximately 700 heavy trucks; over 500 light trucks; almost 800 pieces of heavy motorized equipment; approximately 1000 pieces of light motorized equipment; and over 2000 other pieces of equipment requiring some maintenance. This equipment is distributed throughout the

State, with a similar mix of equipment at each of the 55 maintenance garages.

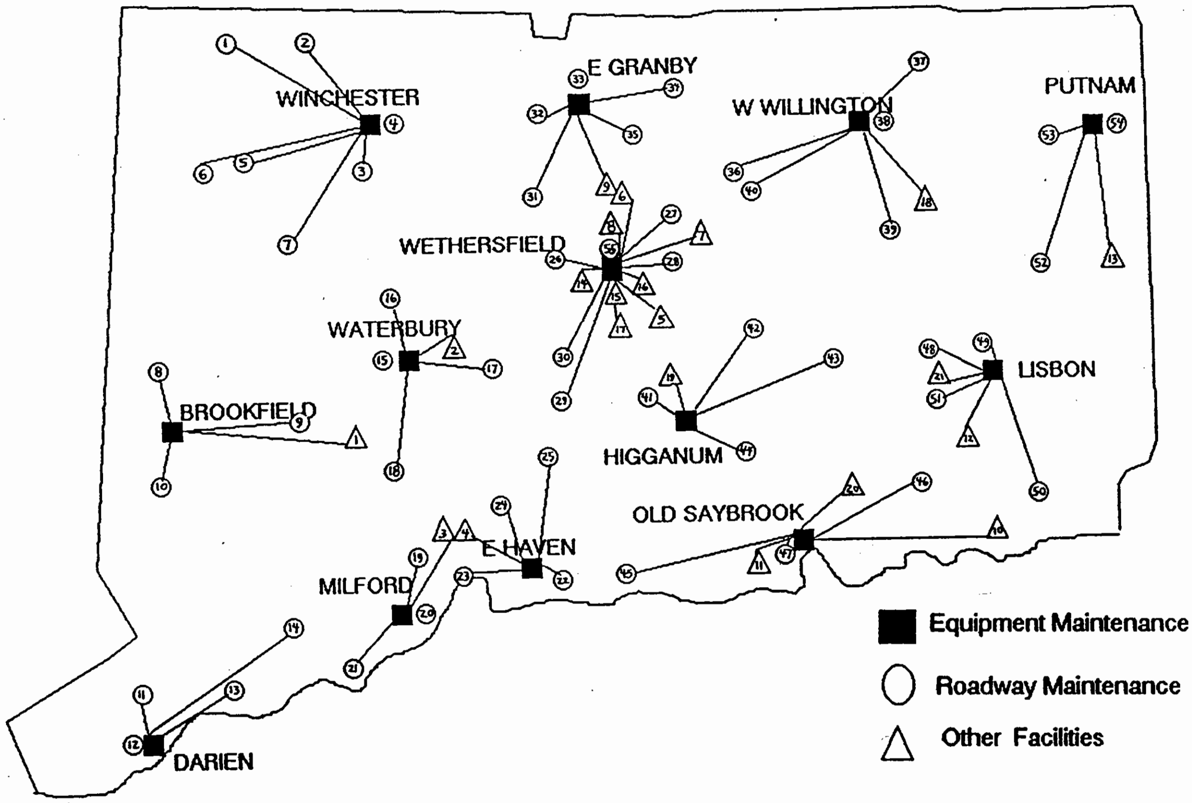


Figure 1. Existing equipment repair system.

Scope and Objectives

It is important to note that this study is predicated on the continuation of certain aspects of the status quo. First, the amount of roadway maintenance performed by the State is assumed to remain at its current level. Second, the number and location of maintenance garages (circles and triangles in Figure 1) are assumed to be fixed. Third, the amount of equipment repairs performed by the State is assumed to remain at its current level. These assumptions allow the analysis to focus primarily on the possibility of consolidating the thirteen equipment repair facilities, which is what this study was charged with investigating.

Significant departures from the status quo may be caused by major changes along any of the following lines:
-- increased use of subcontracting for roadway maintenance;
-- increased use of subcontracting for equipment repairs;
-- increased percentage of repairs performed where equipment is housed; and

-- changes in the numbers and locations of maintenance garages (circles and triangles in Figure 1).

Although changes such as these might be beneficial for the State, determination of possible benefits from such changes is beyond the scope of the current study. In the best of all possible worlds, a comprehensive study would look at all of these issues in conjunction with the question of consolidation of repair facilities. For the current study, conservative assumptions regarding the continuation of certain aspects of the status quo were necessary to enable completion of the project within the required time frame.

In a way, the findings presented in this report could be used to help determine benefits of major changes in maintenance operations. Through cost and demand sensitivity analysis, we explore how the repair facility configuration might change under conditions that correspond to significant departures from the status quo. This analysis is presented in general terms, so that the effects of a wide variety of changes can be inferred. Also included in this study are: 1) a broad review of maintenance-related literature; and 2) a general survey of maintenance operations in other states. Although these could be useful inputs for an analysis of major changes to ConnDOT's maintenance operations, it is the assumptions mentioned earlier pertaining to continuation of the status quo that form the primary basis for the recommendations presented in this report.

One other underlying assumption that should be mentioned up front is that the sites of the existing thirteen equipment repair facilities are assumed to be the only possible locations for repair facilities. Because this research was prompted by Thomas Commission recommendations which suggested consolidation of the existing system, it was not designed to investigate possibilities for constructing new facilities at alternative sites. The model used in this research could be extended to handle alternative repair facility sites, but only the thirteen shown in Figure 1 were considered as possibilities for the current study.

The main objectives of this report are to present specific recommendations regarding consolidation of the repair facilities, and to describe in detail the methods used in arriving at the recommendations. The study centers on an optimization model which has an objective function that minimizes the total costs of the system. These costs, which include equipment transportation costs and overhead costs of repair facilities, are completely detailed within the report. Although the focus is on minimizing costs, a great deal of emphasis is placed on ensuring that maintenance will continue to be performed at the current high level of service. The optimization model used for the study includes realistic constraints to reflect the amount of service required by equipment, and the capacities of the repair facilities to provide that service. The development of the parameters used to represent requirements and capacities are completely explained as part of this report.

Methodology

The nature of the optimization model, which plays a central role in this study, is introduced in this section using a simple example. Figure 2 shows a system composed of three existing facilities (A, B and C) and eight garages (1 - 8) which house equipment requiring service. The straight lines in the figure represent current assignments of garages to facilities. The garages and their equipment repair requirements are assumed to be fixed. In solving this example problem, we must simultaneously decide which of the three facilities should be kept open, and which garages are to be served by which facility.

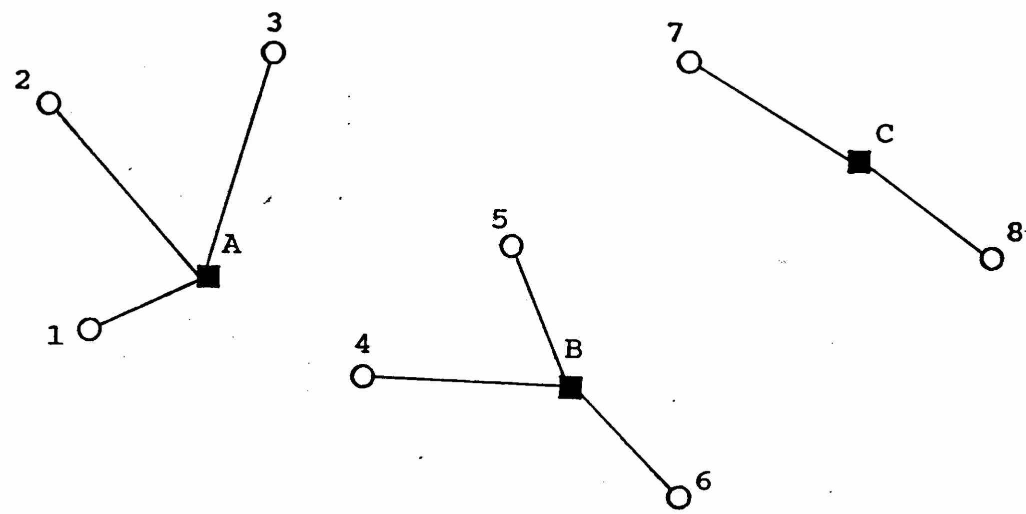


Figure 2. An example system with three facilities and eight garages.

Figures 3 and 4 show two configurations that are alternatives to the existing system. The solution in Figure 3 is one where facilities A and C are kept open, and the garages previously served by facility B are divided between the open ones based on proximity. The assignment of garages to facilities is indicated by the surrounding enclosures.

Note that the solid squares for the closed facilities have been removed from the figures, and each enclosure contains only one open facility. In the solution shown in Figure 4, only facility B is kept open, and all garages are served by that facility. Considering these and other alternatives, how do we go about choosing the best solution?

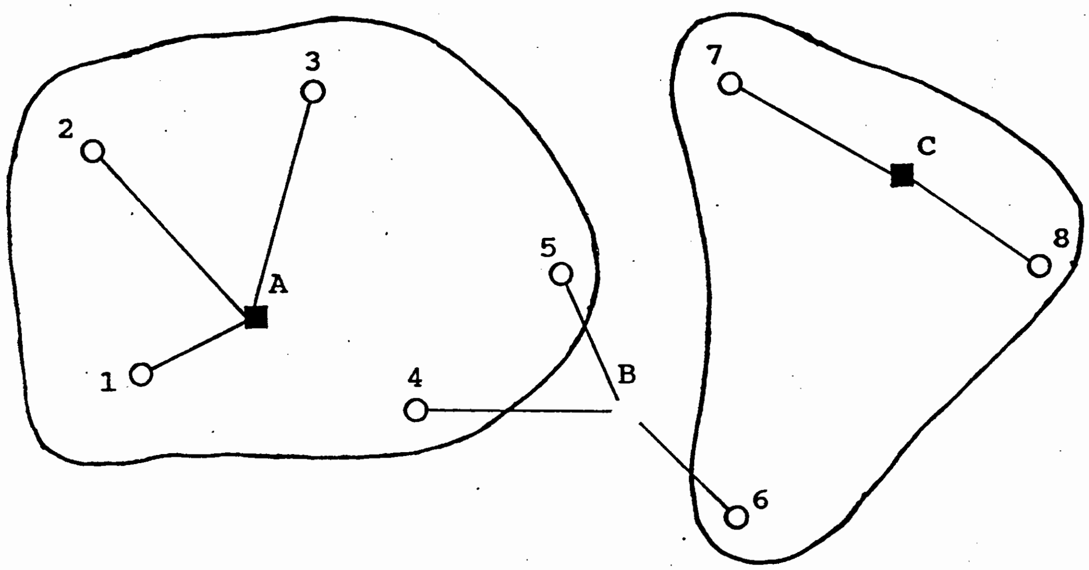


Figure 3. A solution where facilities A and C are kept open.

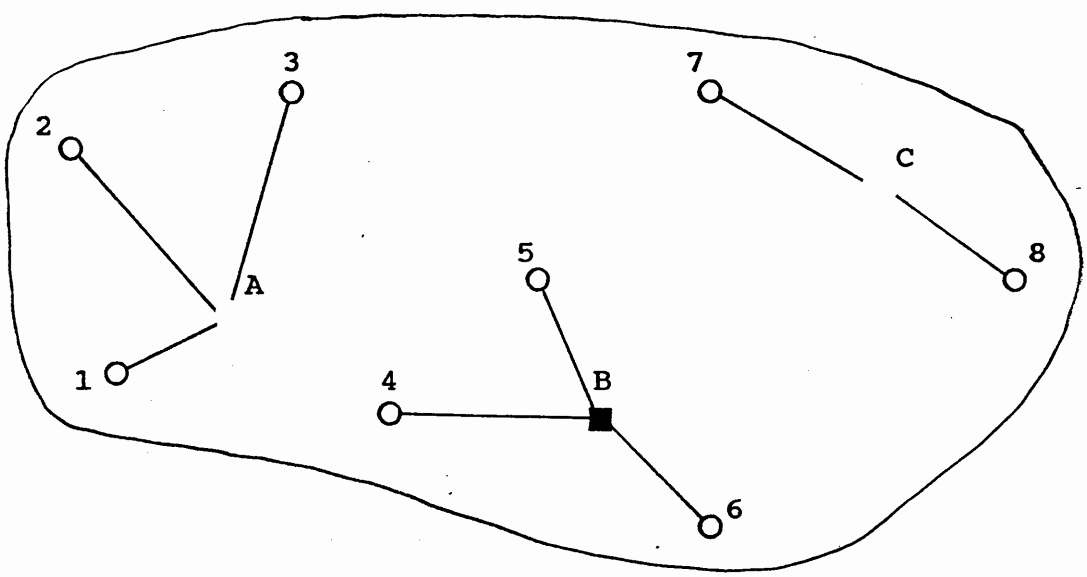


Figure 4. A solution where only facility B is kept open.

The choice of an optimal solution is based on minimization of total relevant costs. In this study, cost components include overhead costs of keeping facilities open, transportation costs for servicing equipment, and expansion costs for adding capacity at open facilities. In the solution shown in Figure 4 where only facility B is kept open, the overhead costs are relatively low, while the transportation costs are relatively high. The configuration in Figure 4 might have expansion costs due to construction required at facility B to enable it to serve all garages' requirements. The solution in Figure 3 probably has higher overhead costs than that in Figure 4 because two facilities are open instead of one; but the transportation costs are lower because many of the garages are closer to the facilities that serve them. Also, the configuration in Figure 3 may require little or no new construction, particularly if there is extra capacity at facilities A and C in the existing configuration. Both of the alternatives shown in Figures 3 and 4 would require reassignment of mechanics from closed facilities, but if we assume that the total number of mechanics will remain fixed, then we can ignore the distribution of mechanics until after a final solution has been developed.

Which solution has the lowest total cost for our simple example problem? This depends, of course, on the relative magnitude of the cost parameters used in the problem's specification. Without getting into the details of cost calculations right now, let us further consider what is involved in solving the example problem. The two types of decisions involved in specifying a solution are: 1) which facilities to keep open; and 2) which facilities serve which garages. These decisions must be made sequentially, since the assignment of garages to facilities depends upon which facilities are available. In fact, once the open facilities have been determined, the problem of assigning garages to facilities is relatively simple. Therefore, one approach to solving the problem is to look at all possible combinations of open and closed facilities, find the associated assignments for each, and then choose amongst them based on total cost. Acknowledging that at least one facility must be kept open, there are only seven combinations of facilities for this example. For this problem, it would be relatively easy to evaluate all possible combinations, and then simply choose the solution with the lowest total cost.

When the number of possible facilities is thirteen, however, evaluating all possible combinations becomes a very time-consuming task, even for a high-speed computer. Fortunately, mathematical programming methods have been developed to arrive at an optimal solution in an efficient manner. In this study, we develop a mathematical programming model and then solve the problem using a personal computer-based optimization package.

Establishing realistic values for the model's cost and capacity parameters has involved a great deal of time and effort on the part of the principal investigators and many people within ConnDOT. Because the recommendations of this study rest upon the input values used as well as the assumptions of the model, we have taken great care to outline these completely within this report. The report also presents results of sensitivity experiments performed to test the robustness of our recommended options as input parameters are varied.

Before going into the details of the model and experimental results, we present a summary of our recommendations.

Summary of Recommendations

The recommendations of this study are presented in the form of two options:

-- Ten repair facilities. As more completely described later, this option is based on optimization runs where any of the 13 existing facilities are eligible for closing, and expansion is allowed at any facility. The net present value of savings for this option is $ 5.01 million.

-- Eleven repair facilities. This option is based on optimization runs which were constrained such that the East Haven facility must be kept open and no expansion could occur at Wethersfield. The net present value of savings for this option is $ 3.12 million.

A summary of both options is presented below, including discussion of the relative advantages and disadvantages of each. The choice between these two options is left to decision-makers who can best represent the interests of the State.

Ten facility option

Figure 5 presents the recommended ten facility option. The main difference between this option and the existing repair system is that the ten facility option contains three less repair facilities (Brookfield, East Haven, and Higganum are eliminated). The elimination of these facilities is accomplished by expanding the roles of six of the remaining ten facilities (the roles are essentially unchanged at East

Granby, West Willington, Putnam and Darien). Construction of new bays is recommended for two of the six facilities that pick up additional loads. The expansions called for are: four new work bays at Waterbury, and five new bays at Wethersfield.

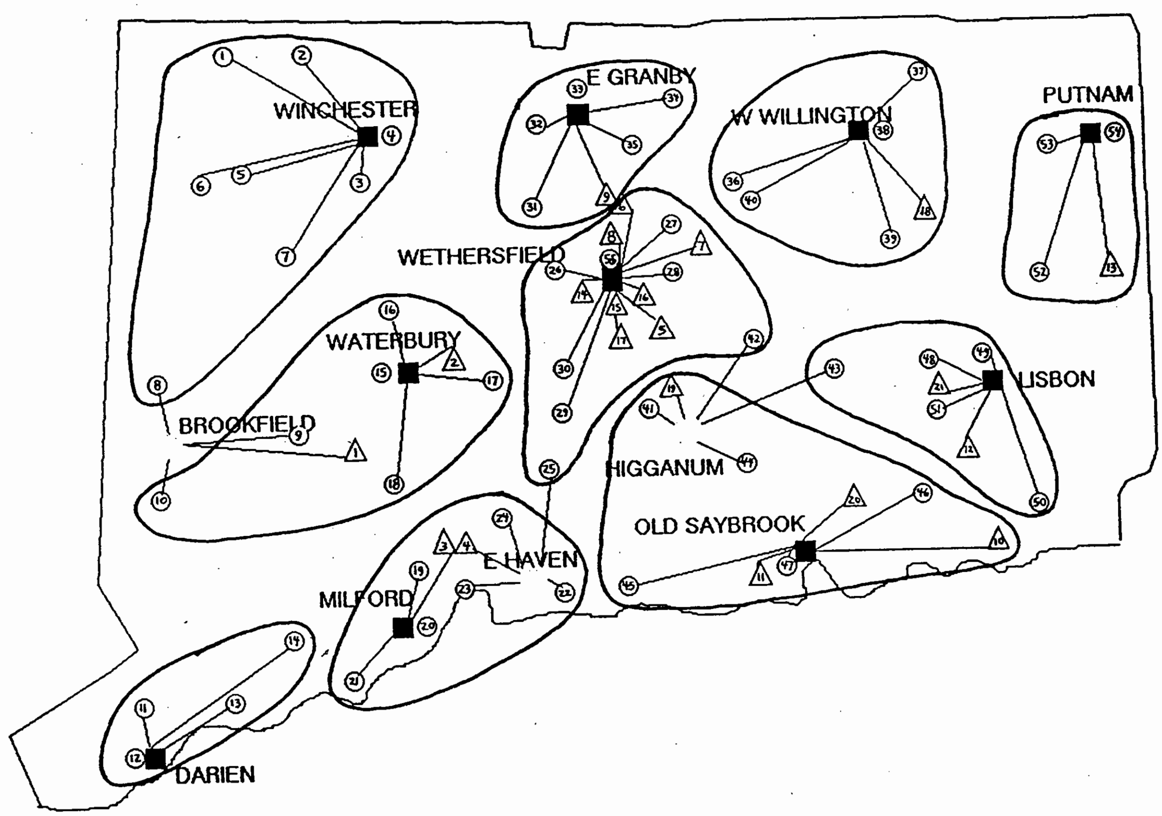


Figure 5. Recommended ten facility option.

Table 1 summarizes the estimated cost changes for the ten facility system, as compared to the existing system. Based on a 20-year horizon, the net present value of the total savings is $ 5.01 million. In the table, these savings are broken down into the three major cost components: overhead, transportation and expansion; and each of these is separated into one-time and annual components.

Table 1. Summary of cost changes resulting from the recommended ten facility option.

	Overhead Costs	Transp. Costs	Expansion Costs	Totals
One-time:	-3,097,000	----	+549,200	-2,547,800
Annual:	-500,200	+233,100	+32,315	-234,785
(& one-time equivalents*)	(-5,247,100)	(+2,445,200)	(+339,000)	(-2,462,900)
Net Present Values:	-8,344,100	+2,445,200	+888,200	-5,010,700

(* one-time equivalents of annual cost changes are based on a 20 year horizon and a 7.125 % annual interest rate)

The majority of one-time savings shown in Table 1 are from revenues resulting from the sale of the Brookfield, East Haven and Higganum properties. Subtracted from this are one-time costs associated with the new construction at Wethersfield and Waterbury. Appendix A presents details of how overhead and expansion cost parameters were developed for this study.

The main additional cost of closing facilities is the increase in transportation costs, as shown in Table 1. Transportation cost estimates, which are functions of travel distances and times, are developed in Appendix C. Although both of the recommended options result in increased transportation costs, in each case these are more than offset by the large savings in overhead.

<u>Eleven facility option</u>

Figure 6 presents the recommended eleven facility option. The major reason for considering this option is that it keeps open the facility at East Haven. ConnDOT maintenance management has identified East Haven as an important facility because it is efficiently designed and strategically located near the busy I-91 / I-95 intersection. The eleven facility option also considers ConnDOT management's concern that construction of additional bays at Wethersfield may not be feasible.

The two facilities closed in the eleven facility option are Brookfield and Higganum. The repair requirements currently served by those two facilities are distributed amongst several of the facilities that remain open. Also, two of the current assignments of garages to open repair facilities are changed (garage 18 and garage 29). These changes enable the closings of Brookfield and Higganum without requiring any expansions at open facilities in the system.

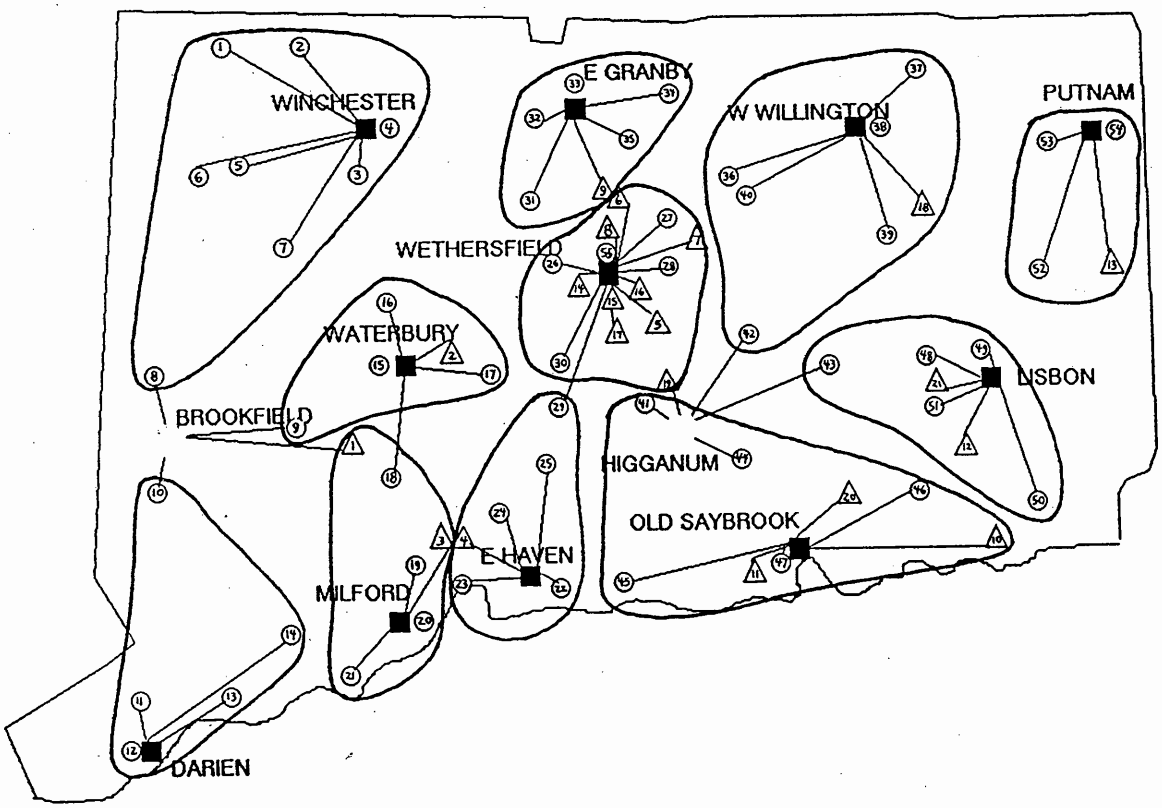


Figure 6. Recommended eleven facility option.

Table 2 summarizes the cost changes for the eleven facility option in the same format as that presented in Table 1. The net present value of the savings for the eleven facility option is $ 3.12 million, which is 62 % of the savings offered by the ten facility option.

The eleven facility option offers several advantages that counterbalance its additional cost. First, no expansions are required at any of the facilities, which enables implementation on a shorter time horizon and with less disruption. Second, as mention earlier, the eleven facility option keeps open the strategically-located East Haven facility. Other advantages of the eleven facility option to be weighed against its additional $ 1.89 million in cost are discussed later in this report.

Table 2. Summary of cost changes resulting from the recommended eleven facility option.

	Overhead Costs	Transp. Costs	Expansion Costs	Totals
One-time:	-1,976,000	----	----	-1,976,000
Annual:	-321,600	+212,500	----	-109,100
(& one-time equivalents*)	(-3,373,600)	(+2,229,100)	----	(-1,144,500)
Net Present Values:	-5,349,600	+2,229,100	----	-3,120,500

(* one-time equivalents of annual cost changes are based on a 20 year horizon and a 7.125 % annual interest rate)

It is important to note that neither of the recommended options correspond directly to any of the "optimal" solutions presented in the results section of this report. While the options being recommended are based on optimization runs, they also reflect important considerations not included in the model. One such consideration is the need to reassign mechanics from the facilities being closed. Although Appendix F presents results useful for planning reassignments, the optimization model has not considered the very real costs involved in this and other implementation requirements. Consequently, the recommended options consider such factors as well as the optimization results.

The summary presented above has merely been an outline of our recommendations. In this report, we will show how the optimization model was used to generate many solutions under different scenarios. The results of all model runs were considered when developing the options displayed in Figures 5 and 6. Section V presents a more complete discussion of the recommended options and the reasoning behind their development.

II. REVIEW OF LITERATURE

Equipment Repair Literature

The mathematical formulation of the present study deals chiefly with the facilities location problem. However, it may also be considered within the broader context of "maintenance management systems" (MMS) and "equipment management systems" (EMS). In the 1950s, Connecticut was one of the first states to begin research into management of maintenance operations. According to Anderson (1984), the basic purpose of a MMS is to control resources to "accomplish a predetermined level of service through planning, budgeting, scheduling, reporting, and evaluating". Unfortunately, the full potential for MMS has not been realized. The systems have been successfully used for planning and budgeting, but there has been little success in using them for evaluating the performance of maintenance crews.

It is important to keep this broader context in mind since any solution to the facilities location problem must be compatible with the overall operating environment of ConnDOT. The literature on both MMS and EMS is extensive. Some of the issues especially relevant to the present work include:

- Productivity standards
- Equipment maintenance standards
- Equipment rental rates and downtime costs
- Roadway maintenance standards
- Contract maintenance

A complete examination of any one of these would constitute an ambitious study in itself. We will confine our present consideration to a brief look at the literature related to each of these.

Productivity Standards

As noted earlier, this study deals primarily with the determination of which, if any, equipment repair facilities should be consolidated in order to minimize "total" costs. In the present case, these are defined as the annualized costs of keeping facilities open (plus expanding selected facilities) plus the overall transportation costs. Our major effort will be in establishing an "efficient frontier" based on "productivity" demonstrated by existing ConnDOT garages. Clearly, if productivity could be improved, the total cost would be reduced.

In a study of shop staffing levels, Ray (1984) notes the dependence of shop performance on (a) "productivity" and

(b) "economic optimization". Simply put, "productivity" refers to getting the most utility from existing resources while "economic optimization" is used to determine the optimum level or distribution of resources to minimize total costs.

Ray (1984) notes that optimum staffing levels are influenced by fleet variables such as age, variation between manufacturers, type of equipment, and fleet utilization characteristics and personnel variables such as "knowledge, skills, and abilities; turnover problems; motivation; scheduling; and shop management."

It might appear that development and application of flat-rate standards would assist in assessing and improving productivity. However, this has been difficult due to options such as repair or exchange, overhauling or rebuilding subsystems and trips to the field. For these reasons and because of the diversity of equipment and demand for service at a state repair facility, it might not be reasonable to expect a state facility to achieve the productivity shown in a flat-rate manual.

Maze (1989) also describes some of the difficulties associated with applying conventional work measurement systems to motor vehicle maintenance. Tasks are non-repetitive with conditions varying from one job to another. For example, to replace a part, bolts may be frozen or may not - resulting in different time and technique required. Also, mechanics are required to do a broad spectrum of work. He cites a Chicago Transit Authority study which estimated that their bus mechanics commonly conduct 1,800 different tasks. "Typically, mechanics in governmental agencies spend only 50 percent or less of their time actually conducting mechanical work." Maze describes two methods, work sampling and time slotting, used for better time management.

Productivity is also the subject of a report by Kazlauskas and Geist (1989) who describe conducting time studies to develop new work standards for Pennsylvania. The standards typically included preventative maintenance and minor repair work on trucks and construction equipment. Several deficiencies in the physical layout of facilities were identified and corrected. Efficiency was also improved by providing proper tools, thus eliminating need for mechanics to borrow.

Melone (1989) describes the development of an equipment management system in Virginia. Much emphasis is given to the comprehensive work order system. He also notes the necessity to develop job standards, and that they should be based on 12 months' worth of data. They plan to use the actual hours worked by all the mechanics at each activity to calculate the standards. These will be used to determine the use of proper procedures and skills of individual employees. "Total hours used in each category will be averaged for each class code of equipment (i.e. pickups, dump trucks, graders, loaders, and mowers)... Downtime will be monitored by checking a block unit 'inoperable.'" Melone notes that total mechanic hours required can be calculated by multiplying average maintenance hours for a given unit class by the number of units in the class and summing over all classes. This figure is then adjusted by a "utilization" factor which is developed for each shop and accounts for actual hours charged to productive work. "Unassigned time would include vacation, sick leave, special nonequipment tasks, and time when no job was assigned although the mechanic was available."

Chambers (1989) describes work performed for the Florida DOT, which has approximately 3000 employees at 32 maintenance yards. Approximately 7,700 pieces of equipment are maintained by about 250 employees at 33 shops. An analysis of three of the maintenance yards "initially identified approximately $1.6 million in excess labor costs throughout the yards, ten percent of which was in the shops." According to Chambers:

> "APC identified approximately $1,975,000 in excess labor in the three yards (120 positions). Through the installation process this labor was redirected toward achieving a higher level of maintenance (improved productivity). Approximately $3,346,000 in additional maintenance is currently being realized on an annualized basis of which $352,000 is in the shops. This increased level of shop activity is being realized after a 36% reduction in shop personnel."

Statewide, Florida could expect $14 to $17 million in increased productivity in remaining 29 yards for which approximately $1,540,000 to $1,870,000 would be achievable in the remaining 31 maintenance shops.

At a 1988 workshop, TRB (1989), 27 problem statements of research needs in equipment maintenance were considered. From these 27, a questionnaire containing 14 questions was distributed to participants. One of the 27 statements <u>not</u> reflected in the questionnaire was "Should mechanic performance (and pay) be based on a flat rate manual developed for government repair systems?". However, the question "Should a catalog of performance standards used for various equipment maintenance tasks be prepared?" was included. It was subsequently voted by participants to be of moderate interest.

According to an article in Better Roads (1987), in North Carolina, the MMS covers 18,000 vehicles. Repair and rebuild codes for each class of equipment "include job standards developed by class of equipment that establish the expected average repair or rebuild time required. Time standards are reviewed against actual time and adjusted periodically." Computerized "exception reports" are used in Georgia to "identify low or unusual time and high repair costs compared to state averages... These reports are used to eliminate unneeded and/or low-use high-downtime equipment to reduce fleet size."

As Anderson (1984) notes, job standards which have been developed based on work studies which directly involve the worker who will implement them are more readily accepted. This report gives much more detail about performance standards. Thus, their use seems feasible for maintenance in general, even if more difficult for equipment maintenance. The study may be relevant in another way also - to provide data relating equipment requirements to performance standards. This could then be used in an overall optimization for equipment assignment.

A detailed analysis by Sanderson and Sinha (1984) for the Indiana DOT made in-state comparisons of productivity in roadway maintenance. Included is an interesting discussion of the effect of equipment/task compatibility on productivity. For example, the authors note that "a shallow patching crew with only a pickup truck would be expected to perform lower quality work than a crew that uses a portable patcher and roller. Examination of these records might indicate a problem of equipment availability or scheduling (underscore ours)." Thus, both the variety of equipment available and equipment downtime are likely to impact productivity of maintenance operations.

Ray (1984) reports that outlying, or secondary, repair shops were tried in Louisiana in an attempt to improve efficiency by bringing repair capability closer to the equipment. However, "difficulty in supplying parts and the administrative overhead associated with small secondary shops has reduced overall efficiency. The travel time saved by secondary shops does not appear to offset the higher operating costs." Centralization within a district is expected to be more efficient. Ray's (1984) analysis indicates that the optimum statewide staff would be 197 welders and mechanics.

In summary, productivity in equipment maintenance operations is important for any highway agency, including ConnDOT. With regard to the present study, increases in productivity would shift the "efficient frontier", result in lower costs, and possibly alter the optimum solution. However, measurement of productivity in equipment maintenance by highway agencies appears to have been very limited. Application of productivity standards is even more limited.

Equipment Maintenance Standards

While it would appear that standards of vehicle maintenance are very important in determining repair capacity, there is little in the literature dealing with optimum preventive maintenance schedules for highway maintenance equipment. Some information on this topic may be found in the bus literature under life-cycle costing.

PENNDOT operates under a hierarchy of state-district-county. As reported by Amos (1984), one of their performance indicators at the county level is equipment utilization, where the hours per unit for each equipment type is compared against the statewide average.

As observed by Melone (1989), the use of a good preventive maintenance program with scheduled servicing will tend to reduce the breakdown of equipment and increase planned maintenance. He recommends several rules-of-thumb for scheduling. For example, service and preventive maintenance should comprise the base schedule of production and represent more than 50% of average daily work. If a unit is in an unsafe condition or is inoperable and is needed for production, it should have a high priority. Low priority will be assigned to seasonal repair work. He also notes that "During peak periods some work will be backlogged, requiring other decisions (i.e., overtime, hourly employees, transfer of mechanics for work, and use of commercial facilities)." An exception report titled "suspended" will be developed for the purpose of identifying equipment that remains unrepaired because of unavailable parts, high cost, etc.

An evaluation of the FHWA Equipment Management System (EMS) Manual was conducted by the Arkansas State Highway and Transportation Department. In a description of the experience, Nielsen (1984) defines equipment management as "the process of managing equipment resources to achieve maximum availability and productivity at the lowest overall relative cost." A critical element is an effective preventive maintenance program. Among other things, this program "outlines a simple system for planning and scheduling periodic service and reporting equipment deficiencies." The equipment management system consists of 4 subsystems:

- Parts and Inventory System

- o Equipment Maintenance and Operations Cost System (EMOCS)
- o Equipment Cost Accounting System
- o Equipment Control System

The EMOCS includes consideration of repair shop resource allocation and control of both scheduled and non-scheduled repair. It also tracks equipment downtime.

The Nielsen report also contains several tables on such statistics as fuel consumption, miles operated, age of equipment, etc. There is a total of 5247 equipment units, of which 1049 are large trucks, 206 are autos, 138 are station wagons, and 236 are carryalls and vans.

An article in Better Roads (1989), describing the results of a nationwide survey of equipment managers, provides some additional insight into the overall problem of maintenance. Nearly half of the managers "cited the difficulties in finding and keeping competent workers, dealing with top departmental management, and training personnel as their most critical problems." Although respondents noted that upper management is often not aware of importance of preventative maintenance, it might be that this is due to the failure of middle management to adequately support the case. It is noteworthy that, while the managers surveyed recognized the need for such innovations as more sophisticated scheduling, they did not place a high priority on it.

According to Better Roads (1987), Ohio, like Connecticut, is developing an in-house EMS. Their system costs less than $300,000 vs. an estimated $1.5 M for an off-the-shelf system. It was implemented at the central garage in May 1987. Daily transactions are entered at district garages, but smaller county garages and outposts must send in information for input. Elements of the ODOT EMS show it to be similar to CONNDOT's "PM Planner":

- o On-line equipment inventory
- o On-line parts inventory
- o Repair work order system
- o Preventive maintenance system
- o Fuel, oil and coolant transactions
- o Ability to produce a variety of reports

Preventative maintenance records for equipment are updated during fueling. The system then calculates when inspections are due based on miles, hours, or time.

The Better Roads (1987) article also describes equipment management systems used, or under development, by Illinois, Kansas, and Florida. The Illinois system contains records of equipment utilization reports covering equipment type and highway maintenance work activity. In Florida, an "automated warehouse system" will have terminals in both the warehouse and shops of its 34 locations.

Thus, a review of the literature supports the view that CONNDOT has in place several (and is implementing additional) elements of a maintenance management system that compares well with the state-of-the-art for highway agencies. While much has been done by CONNDOT and other highway agencies, there would appear to be several areas, such as scheduling, resource leveling, and optimization in preventive maintenance, that have the potential to produce savings and should be examined in future studies.

Equipment Rental Rates and Downtime Costs

Obviously, equipment costs are important. One means of accounting for costs is through assignment of rental rates. An additional related item of interest is the cost of downtime. Both of these are considered in this section.

The article in Better Roads (1987) describes rental systems used by Washington State DOT and the Kentucky Transportation Cabinet. Washington has a "Transportation Equipment Fund" which operates like a rental car system. Dual rental rates are established for each unit. One rate is based on time and covers such things as depreciation; another is based on miles or hours operated and covers fuel, oil maintenance, and repair. The Kentucky Transportation Cabinet utilizes an equipment rental system where the user is assessed a rental on those pieces of equipment that fail to generate enough revenue to cover fixed cost (including depreciation and equipment overhead). As with other systems, the EMS also generates reports, including such factors as downtime on equipment.

Ray (1984) studied queuing behavior and proposed that arrival rates could be approximated by a Poisson distribution. The differences that arose were due to such practices as, for example, bringing in all mowers at the same time.

Determination of costs of downtime is somewhat difficult, since equipment-related delays do not always result in delays in planned maintenance activities. As noted by Ray (1984), "the disruptive effect of equipment downtime can often be countered by supervisor action, including planning of alternate activities, use of substitute equipment, and use of alternate procedures. Downtime in the shop, however, can be accurately measured and a cost penalty can be applied. If it can be assumed that enough second-line equipment units are available to mitigate the effects of downtime, the cost of shop downtime becomes the cost of maintaining second-line equipment."

Roadway Maintenance Standards

ConnDOT has many responsibilities in the area of roadway and bridge maintenance. These include, but are not limited to, roadway surface (pavement) management and other maintenance activities such as snowplowing, mowing, drainage, maintenance of traffic control devices, accident cleanup, hazardous spills, and repair of safety appurtenances. These activities are primarily affected by the location of the roadway maintenance garages, as opposed to the equipment repair facilities. One qualitative appraisal of location effects is supplied by a 1989 study for the Iowa Department of Transportation by Wilbur Smith and Associates (1989). In that work, the public's perception of importance of maintenance operations was examined in Iowa and other states. It was found that "approximately 50% of the current facilities are inadequate." With regard to facility location, it was concluded that while the public doesn't want the locations to be changed "approximately 40% of the present facilities are not needed as the level of maintenance services now being provided can be matched or improved upon by operating larger, more productive crews that are based from adequate maintenance facilities."

The constraints in the mixed integer programming formulation are based on providing the existing levels of service for both equipment and, indirectly, the highway system. Clearly, if standards of equipment and/or roadway maintenance are changed, the "optimal" facility location solution may change. However, as noted above, the direct effect of changes in service standards would be most apparent in the optimum location of roadway maintenance facilities. Of course, this would, in turn, affect the optimal solution to facility location. Our approach here has been to assume the existing locations of roadway maintenance garages as fixed.

Nationally and in Connecticut, much work has been done over the last 15 to 20 years on pavement management. Included in this category are several reports, Stephens et al (1983), Davis et al (1989) and Davis and Van Dine (1991), prepared for ConnDOT and culminating in a micro-computer version of a network optimization which minimizes roadway user "disutility" given constraints on budgets for maintenance and reconstruction. The relevance of this optimization to the present study lies in its specification of optimum roadway maintenance levels and programs for achieving these optimums. For example, if added travel time leads to difficulties in achieving optimum roadway maintenance levels, it might very well be seen as an objection to consolidation of repair facilities. Conversely, as further described by Davis and Van Dine, among the required inputs to that model are estimates of costs of performing various roadway pavement maintenance activities. While the assumptions of equipment availability implicit in these costs would be affected by the facility location solution, it is probable that any effects would be within the inherent error of the cost estimates.

Contract Maintenance

In a discussion of contracting for public services in general, McMullen (1986) notes an number of pros and cons associated with the practice. Included in the arguments against the practice are such considerations as "the function to be contracted is so vital that it can only be satisfactorily performed by public employees..." Cost-effectiveness is also questioned and past examples of corruption are cited. In counter arguments, proponents cite numerous examples of successful contracting for public services, including equipment maintenance. However, with the exception of specialized tasks such as windshield repairs, contracting for equipment maintenance by highway agencies is apparently not common.

On the other hand, contracting (with the private sector) for highway maintenance is common. The report by McMullen (1986), based on responses to a survey of 48 states, the District of Columbia, Puerto Rico, 5 provinces and 20 local governments, showed that 71 of the 75 agencies responding contracted some aspects of highway maintenance. The activities most frequently contracted were associated with pavement maintenance; those least frequently contracted dealt with drainage. To the extent that contracting reduces the number of vehicles that must be maintained, the practice is pertinent to the present study. The reasons for contracting are varied. In some cases, cost is the deciding factor. In most cases, the reason given was lack of required personnel. In many instances the need for special skills and equipment leads to contracting. According to the survey, Connecticut is very close to the "average" in the amount of contracting. However, the survey data indicate no contracting for snow and ice removal. It was our understanding that such contracting does occur. The "average" of the New England states suggest that contracting is somewhat more common in that region than nationally, but there is a significant variation, with Massachusetts contracting far more than any other state and Maine contracting considerably less than the national average.

"The need for contracting should be based on work load and agencies should consider the annual work program, the resources required, and the availability of those resources. Feasibility determination involves the suitability of the activity for contracting, the capability of the agency to develop and manage the contract, and the availability of contractors. Desirability involves a consideration of agency objectives, management concerns, and anticipated costs." In deciding to contract, all agencies make cost comparisons between in-house and out-house. 54 of the 57 agencies responding to this section of the questionnaire used the cost of equipment rental as part of their calculations. Only a few of the responses provided information on the benefits from contracting. Included in the list for those who did respond was "Elimination of the need to purchase and maintain specialized equipment that has limited use." For cost comparisons, the following categories should be used:

- Direct costs - Those costs involved directly with the activity and which would not occur if the activity did not occur
- Variable overhead costs - That proportion of overhead costs that are incurred only because a particular activity takes place,
- Fixed overhead costs - those costs that would accrue irrespective of the decision to undertake the activity with public works forces or with contractors.

According to Blaine (1984), the Ontario Ministry of Transportation makes extensive use of contractors. This occurs primarily with winter maintenance and with a limited amount of summer maintenance. Blaine gives details of the cost analysis (including equipment costs) leading to the decision to contract. He notes that the availability of contractors' crews and equipment during the winter months has led to "considerable" savings and that "more than 20 percent of all Ministry maintenance operations are now performed by private contractors." Nearly all of the Ministry's 800 salt spreaders are mounted on contractors' trucks. Of the 280 large loaders required for winter maintenance, half are rented. In addition, contractors' trucks carry most of the Ministry's salt spreaders. Blaine notes that the 50 km/h average speed of contactor plows is only 3% slower than MTC plows. Smaller jobs such as picnic area maintenance are easy to contract because only a pick-up is needed and the work is often done by students. As with other examples, this tends to level worker requirements.

Blaine (1984) reports that there were "substantial" advantages to contracting out some equipment repairs even though "the cost of repairs in the Ministry garages was usually competitive." Many agencies find that specialized repairs, such as glass installation and wheel alignment can be done at lower cost by private garages. To this list, Ontario adds such jobs as fuel-injector servicing, body work, and painting. On the other hand, since most of Ontario's fleet of snowplow trucks has the same engine, transmission, rear axle, and alternator, repairs to these usually can be performed at less cost in-house. Of particular note is Blaine's (1984) observation: "The Ministry has considerably reduced the time spent by its mechanics traveling to service equipment in the field and transporting equipment into the district garages."

Facility Location Literature

The optimization model used for this study has been built with the same kind of structure found in a broad class of models that are designed for general facility location problems. A comprehensive review of facility location models was performed by Aikens (1985). In that review, models were characterized using the following dimensions: number of facilities, presence of capacity constraints, number of echelons (levels), number of commodities, and whether the model is static or dynamic.

Each of these dimensions will be discussed as they pertain to the model used in this study. For the number of facilities, the categories are: 1) single facility, and 2) multiple facility. The repair facility location problem obviously falls into the second category.

Among facility location models, capacity constraints on the facilities are either included or not. For our application, capacity constraints are important because each facility is limited in the amount of equipment it can repair.

The number of echelons in a system refers to the number of levels for which location decisions must be made. In ConnDOT's repair system there are actually two levels of facilities: 1) the repair facilities where equipment is serviced, and 2) the maintenance garages where equipment is housed. However, because this study takes the location of the maintenance garages as fixed, the problem is properly modeled using a single-echelon system. If the location of the maintenance garages were also being determined, then a more complex two-echelon model would be required.

The "commodity" offered by the repair facilities is equipment maintenance, and because all facilities offer the same set of services the system can be represented using a single commodity formulation. Multi-commodity models allow situations where some facilities offer only a subset of all available commodities. In using a single commodity formulation, the assumption is made that all facilities will continue to offer all types of repair services.

The question of whether a static or a dynamic model is applicable depends upon anticipated changes to the system over time. For example, if greatly increased loads are expected in future years, then a configuration of facilities which changes over time would be appropriate. Although repair requirements in the ConnDOT system may change over time, the changes are not expected to be dramatic enough to warrant the use of a dynamic facility location model. For the purposes of this study, a static model is used to provide recommendations for a single configuration which would be expected to remain essentially the same for many years.

In terms of the dimensions defined by Aikens (1985), the characteristics of the facility location problem of interest to this study are summarized as follows: multi-facility, capacitated, single-echelon, single-commodity, and static. Aikens refers to this problem as SCFL, which stands for "static, capacitated facility location," and the same acronym will be used here. The following general formulation applies for this problem:

(SCFL)

$$\text{Minimize} \quad \sum_{f \in F} \sum_{i \in I} C_{fi} X_{fi} + \sum_{f \in F} K_f Y_f \qquad (1)$$

Subject to:

$$\sum_{i \in I} D_i X_{fi} \leq P_f Y_f \qquad f \in F \qquad (2)$$

$$\sum_{f \in F} X_{fi} = 1 \qquad i \in I \qquad (3)$$

$$X_{fi} \geq 0 \qquad f \in F \; i \in I \qquad (4)$$

$$Y_f \in \{0,1\} \qquad f \in F \qquad (5)$$

Where:

X_{fi} = the proportion of customer i's demand satisfied by facility f;

Y_f = 1 if facility f is established, 0 otherwise;

C_{fi} = the total production and distribution costs for supplying all of customer i's demand from facility f;

K_f = the fixed cost of facility f;

D_i = the demand of customer i;

P_f = the capacity of facility f;

F,I = the sets of candidate facilities and customers, respectively.

In the objective function, (1), the costs must be on a common time basis, e.g. annual production and distribution costs and annualized fixed costs.

Constraint set (2) ensures that the capacity of each facility is not exceeded if it is opened, and it also guarantees that no customers are served by a facility if it is closed (i.e. $Y_f = 0$). Constraint set (3) ensures that all customer demand is met, and constraints (4) and (5) are standard non-negativity and integrality constraints, respectively.

In the literature on facility location models, there is a good deal of information regarding the estimation of model parameters. Each of the cost parameters can have several components. For example, the fixed cost of facility f, K_f, could reflect both a one-time construction cost plus a stream of annual fixed overhead expenses.

A key component of the C_{fi} parameters are costs associated with transportation. Transportation costs are typically assumed to be proportional to distance. Love, Morris and Wesolowsky (1988) discuss various methods for estimating distance in the absence of complete information.

Methods of estimating cost parameters for the repair system model are presented in the Appendices of this report. By defining parameters appropriately, this study adapts SCFL to reflect the key aspects of the equipment repair system.

Much prior research has focused on the development of efficient algorithms for solving SCFL. Examples of this type of research include Akinc and Khumawala (1977), Geoffrion and McBride (1978), and Guignard and Opaswongkarn (1990). Geoffrion and McBride (1978) provide a generalized version of the formulation which allows for side constraints and lower bounds on facility output. These additional constraints are easily handled by the Lagrangean relaxation solution technique they develop.

Although much progress has been made on developing faster solution techniques to optimally solve SCFL problems, algorithmic efficiency is not a major concern for the current study. With 13 existing facilities in the repair system, the size of the problem is within the capabilities of off-the-shelf, personal computer-based software for mixed integer programming. Therefore, research on SCFL that emphasizes applications is more relevant for our purposes than research directed at improving computation times.

Applications of particular interest are those involving decisions made for systems where facilities already exist. Economides and Fok (1984) consider a problem where four options are available regarding the location of a single warehouse facility. The options are: 1) same location, same technology; 2) same location, new technology; 3) new location, same technology; and 4) new location, new technology. The allowance for a different operating technology can be included in a multi-facility model such as SCFL by adding another subscript to the Y variables. That is, Y_{fj} could be defined as an integer variable that equals 1 if a facility is opened at site f with technology j, and 0 otherwise. This change to the basic formulation increases the number of integer variables, but it does not present a major departure from the general SCFL framework.

Gelb and Khumawala (1984) describe the use of a facility location model for reconfiguring sales regions for an insurance company. In their application, the old configuration consisted of 16 regional offices, and the recommended configuration increased the number of offices to 25. To adapt a mixed integer programming model, a finite number of potential office sites had to be identified in advance. Fixed costs in their formulation were similar to those in SCFL, with some modifications to reflect that some facilities already existed. Variable costs (i.e. C_{fi} values) corresponded to lost sales associated with greater travel distances, as opposed to the production and distribution costs present in the standard SCFL problem. For this model, lost sales as a function of travel distance were established based on data from the existing 16 facilities.

Related to the problem of locating with respect to existing facilities is the problem of capacity expansion. Luss (1982) presents a survey of capacity expansion research, with emphasis on dynamic (i.e. multi-period) formulations. With regard to multiple facility location problems, he states that: "Only a few studies impose upper bounds on facility sizes, and even fewer have facility sizes as decision variables." With respect to SCFL, alternative facility sizes can be handled in a manner similar to the way that Economides and Fok (1984) handled alternative technologies. The integer variables in the formulation are well-suited for modelling expansion cost functions, which Luss (1982) indicates are typically concave. The manner in which SCFL is augmented to handle alternative facility sizes for the current study is discussed in detail in the next section of this report.

Bell and Rainer (1980) performed another applied facility location study. This application is particularly noteworthy because it involved the location of garages for a roadway maintenance system in Alabama. Unlike the ConnDOT application, this study was concerned with locating garages with respect to the roadways being maintained. Rather than solve for which of the existing garages to keep open, the study evaluated alternative configurations which were generated manually. Evaluations were done using linear programming software to solve the transportation problem that results when the Y variables in the SCFL formulation are fixed at values of either 0 or 1. Bell and Rainer (1980) reported that the study resulted in the closing of 4 out of 47 garages in Alabama, with associated annual cost savings of over $240,000.

III. OPTIMIZATION MODEL

In this section, the optimization model is specified and model parameters are discussed. The optimization model used in this study is a variation of the SCFL model presented in the previous section. Using notation similar to that presented for SCFL, the mixed-integer programming model, labeled MIP, is presented as follows:

(MIP)

$$\text{Minimize} \quad \sum_{f=1}^{13} \sum_{i=1}^{76} C_{fi} X_{fi} + \sum_{f=1}^{13} (K_f Y_f + M\, A_f + N\, B_f) \qquad (6)$$

Subject to:

$$\sum_{i=1}^{76} D_i X_{fi} \leq (P_f Y_f + R\, A_f + S\, B_f) \qquad f=1 \text{ to } 13 \qquad (7)$$

$$\sum_{f=1}^{13} X_{fi} = 1 \qquad i=1 \text{ to } 76 \qquad (8)$$

$$A_f \leq Y_f \qquad f=1 \text{ to } 13 \quad (9)$$

$$B_f \leq 8\ A_f \qquad f=1 \text{ to } 13 \quad (10)$$

$$B_f,\ X_{fi} \geq 0 \qquad f=1 \text{ to } 13,\ i=1 \text{ to } 76 \quad (11)$$

$$Y_f,\ A_f \in \{0,1\} \qquad f=1 \text{ to } 13 \quad (12)$$

Where the following are decision variables:

X_{fi} = the proportion of garage i's repair requirements satisfied by facility f;

Y_f = 1 if facility f is kept open, 0 otherwise;

A_f = 1 if two work bays are added at facility f, 0 otherwise;

B_f = number of work bays added, above two, at facility f.

The following are model parameters:

C_{fi} = the total annual cost of transporting all equipment from garage i to facility f for repairs;

K_f = annualized cost of keeping facility f open;

M = annualized cost of adding two bays at a facility;

N = annualized cost of adding each bay above two at a facility;

D_i = total equipment repair requirements at garage i;

P_f = repair capacity, in terms of equipment serviceable, if facility f is kept open.

R = repair capacity added by adding two bays;

S = repair capacity added for each bay above two added at a facility.

In this formulation, f indexes over repair facilities and i indexes over garages. As in the SCFL formulation, (6) reflects total annual costs, (7) ensures that capacity is not exceeded at any facility, and (8) specifies that each garage's repair requirements must be met. MIP differs from SCFL primarily in its allowance for alternative capacity configurations at each facility.

To illustrate how the capacity options work, consider a single facility, e.g. facility 1. If facility 1 is kept open with its existing number of work bays, then Y_1 would equal 1, the capacity of the facility would be P_1, and the associated annualized costs would be K_1. Alternatively, if we assume that an expansion of two bays (the minimum allowable) is implemented at facility 1, then both Y_1 and A_1 would equal 1, the capacity of the facility would be (P_1+R), and the annualized costs would be $(K_1 + M)$.

Constraint set (9) ensures that a two-bay expansion can only occur if the facility is kept open. An expansion above two bays at facility 1 requires values of 1 for both Y_1 and A_1, and then a non-zero value of the B_1 variable. For example, a four bay expansion at facility 1 would be indicated by the following values of the decision variables: $Y_1 = 1$, $A_1 =1$, and $B_1 = 2$. Constraint set (10) ensures that expansions above two bays can only be done if the initial two-bay expansion is included in the solution. This enables a concave expansion cost function to be incorporated into the model. Using the constant 8 in the right hand side of (10) constrains B_f to be less than or equal to 8, which means that expansions are limited to a maximum of 10 new work bays at each open facility. Values for M and N, the expansion cost parameters, are discussed in Appendix A.

B_f variables are continuous, which means that fractional values can result for numbers of bays above two. Continuous B_f variables were used to reduce the number of integer variables in the model, enabling much faster solution times. Because the value of N used for this study is small compared to other costs, the effects from rounding fractional expansion bay values are relatively minor.

The details of how cost, capacity and demand parameters were established are presented in appendices at the end of this report. Appendix A deals with the K_f, M and N parameters; it describes how overhead expenses, construction costs, and/or property values are all considered. Appendix B presents the methods behind the estimation of the P_f, R, S, and D_i parameters. Extensive use was made of data from the existing repair system for the purpose of estimating these parameters. Finally, Appendix C presents the techniques used to establish the C_{fi} values, including discussion of the methods used to estimate travel distances and times.

Each C_{fi} value reflects the cost of all equipment from garage i going to facility f for repair. However, the definition of the X_{fi} variables allows the repair requirements of a garage to be serviced by two or more repair facilities. While the MIP formulation allows fractional X_{fi} values, it will be seen in the next section that few fractional values occur in optimal solutions. From a practical standpoint, any fractional X_{fi} values in a solution can be rounded to 0 or 1 if warranted by managerial considerations. Minor adjustments could be made to a solution to accommodate refinements such as this.

To obtain solutions, a software package called "GAMS" (General Algebraic Modelling System) was used to solve the MIP problem. For reference, a description of the package, a copy of the model, and an output report for GAMS are included in Appendix D. The mixed integer programming model developed in this section can be seen in the GAMS format beginning near the bottom of page D.15. Results based on multiple runs of the program are summarized in the following section of this report.

IV. RESULTS

This section describes the solutions resulting from various runs of the model under different scenarios. The description of the scenarios and presentation of a summary of results are the main purposes of this section. More detailed results are given in Appendix G, where solution summary pages are presented. Discussion of recommendations based on results is deferred until Section V, so as to separate conclusions from results of model runs.

The runs conducted for this study are broken down into four sets. The main set of runs uses the parameter estimates presented in Appendices A, B and C. The constrained run set also uses these parameters, while supplementing the model formulation with additional constraints identified as important by ConnDOT maintenance management. The other two sets vary cost and demand parameters to investigate the sensitivity of solutions to changes in input values. Table 3 summaries the nature of each of these run sets. The presentation of the remainder of this section is structured around these sets.

Table 3. Description of four run sets.	
Set of Runs	Factor(s) Varied
1) Main	Number of Facilities
2) Constrained	East Haven forced into solutions and no expansions permitted at Wethersfield
3) Cost Sensitivity	Transportation Costs and Overhead Costs
4) Demand Sensitivity	Equipment Repair Requirements and Transportation Costs

Main Runs

The main runs use the parameter values presented in Appendices A, B and C, which are values representing the best available estimates of costs, demands, and capacities. The first run in the main set was performed without any restriction on the number of facilities to be present in the solution. This run resulted in an optimal solution with seven open facilities. This solution is shown in Appendix G on the solution summary page labeled "Main, unrestricted."

To provide a basis for comparing the optimal solution, the model was rerun using the same parameters, but the following additional constraint was added:

$$\sum_{f=1}^{13} Y_f = T \tag{13}$$

Where T is a prespecified number of facilities which must be open in the optimal solution.

In the GAMS model presented in Appendix D, this additional constraint appears on page D.16 and is labelled "TOTFAC," since it constrains solutions to have a specified number of total facilities.

Since the optimal solution to the unrestricted problem has seven open facilities, the relevant values of T for subsequent runs are eight through thirteen. Solution summary pages for these runs are labeled "Main, 8" through "Main, 13" in Appendix G.

Table 4 and Figure 7 summarize the savings resulting from different numbers of facilities in the main runs. For this, the optimal solution to the problem with T = 13 is used as a basis for comparison. The optimal 13-facility solution is different from ConnDOT's existing system because certain assignments of garages to repair facilities are different (see the solution summary page for Main, 13). Based on the cost parameters of our model, the optimal 13-facility system has an annual total cost which is about $ 58,800 less than that of ConnDOT's existing system. Because changes could be made to the existing system without closing any facilities, we have chosen to use the <u>optimal</u> 13-facility system as the basis for comparison when evaluating the attractiveness of closing facilities. Therefore, the savings shown in Table 4 and Figure 7 are relative to the optimal 13-facility system.

Table 4 also presents information regarding the <u>marginal</u> savings achieved for each reduction in the number of facilities. Note that each reduction in facilities results in less savings than the prior reduction. Also, there are large drops in marginal savings at certain points. For example, the reduction from 10 facilities to 9 captures only 15 % of the possible savings, whereas the reduction from 11 to 10 captures 19 %. The change in the marginal savings below 10 facilities makes the 10-facility solution an important one to consider. Consequently, in both of the sensitivity run sets, optimal 10-facility solutions are considered as points of reference, along with optimal 13-facility solutions.

This concludes the summary of results from the main set of runs. Further discussion of these results can be found in Section V.

Table 4. Summary of savings for each of the main runs.

Number of Facilities	Net Present Value of Savings	% of Possible Savings	Marginal % Savings
7	$ 7.11 million	100 %	
			5 %
8	6.76	95 %	
			12 %
9	5.87	83 %	
			15 %
10	4.83	68 %	
			19 %
11	3.50	49 %	
			21 %
12	1.97	28 %	
			28 %
13	0	0	

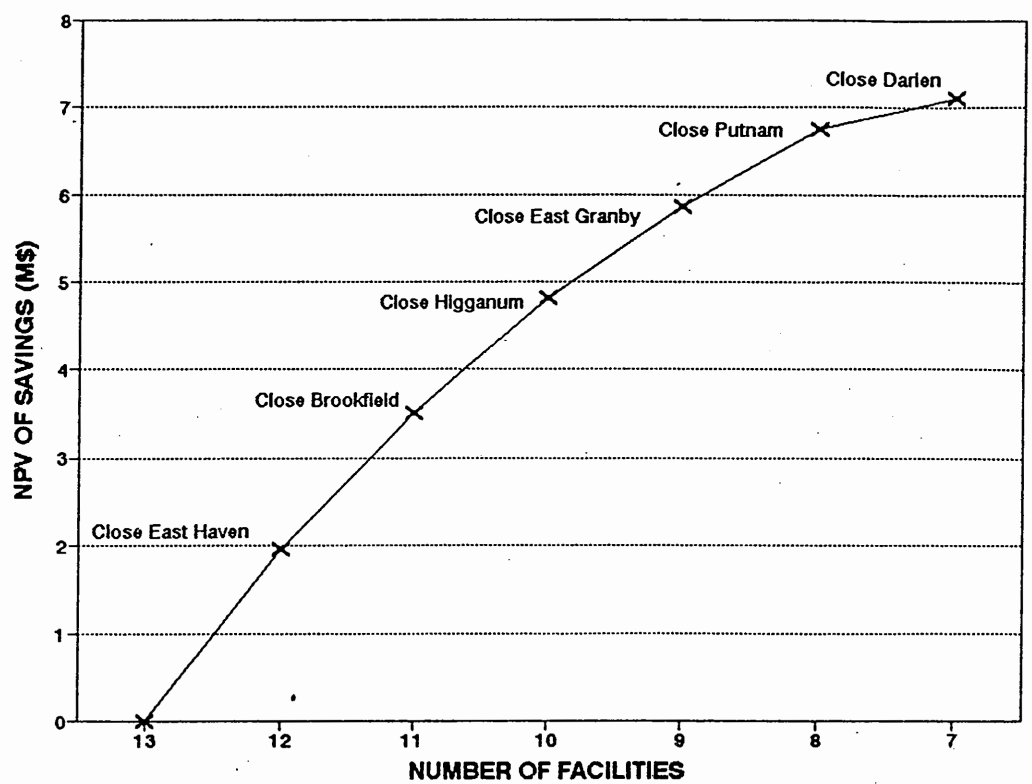


Figure 7. Net present value of savings, based on main runs.

Constrained Runs

The design of the constrained run set is based on feedback obtained from ConnDOT maintenance management after they were presented with recommendations based on the main runs. The feedback focussed on two primary concerns:
1) the closing of the East Haven facility; and
2) expansions at the Wethersfield site.

The first concern stems from the fact that the East Haven facility is considered to be one of the best in the State's equipment repair system because it is efficiently designed and strategically located. These factors, coupled with a concern about a large increased load at Milford, motivated the investigation of solutions where East Haven is kept open.

The concern about expansions at Wethersfield is because that facility is located in an area which is largely residential. Increased traffic flows would not be appreciated by the facility's neighbors. ConnDOT maintenance management is also concerned about limits on the space available at the site, which already houses the largest repair facility in the State.

Given these concerns, the constrained run set was designed to look at the two issues both individually and together. In Appendix G, solution summary pages for runs which disallow expansion at Wethersfield are labelled WETH, unrestricted; WETH, 8; WETH, 9; etc. Those that represent runs where East Haven is constrained to remain open are labelled with the prefix EHAV. Solutions based on no expansion at Wethersfield and keeping East Haven open are labelled EHAV/WETH. Table 5 summarizes the results of these runs, and Figure 8 presents the results graphically. In Appendix G, solution summary pages are not presented for constrained runs that result in the same solutions as other runs (e.g. WETH, 11 is the same solution as Main, 11, as indicated by the savings shown in Table 5).

Table 5. Net present value of savings for constrained runs (all values are in millions of dollars).

Number of facilities	Main	WETH	EHAV	EHAV/WETH
7	$ 7.11	$ 6.32	----	----
8	6.76	5.91	$ 5.82	$ 5.21
9	5.87	5.46	5.07	4.70
10	4.83	4.57	4.15	3.98
11	3.50	3.50	3.16	3.09
12	1.97	1.97	1.60	1.60
13	0	0	0	0

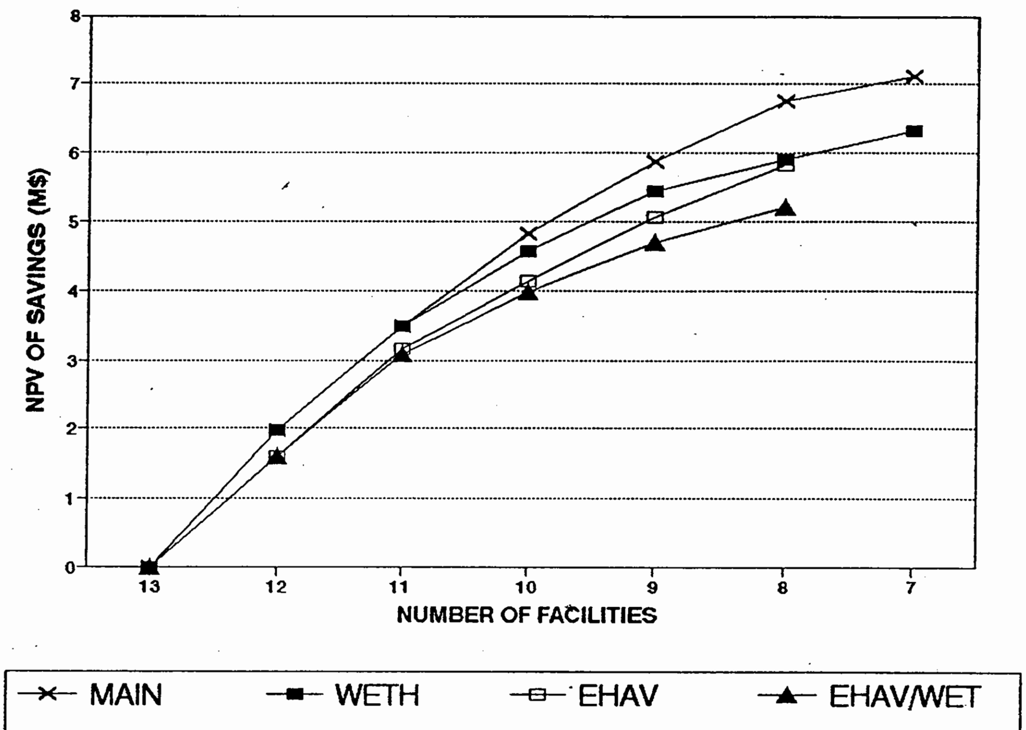


Figure 8. Net present value of savings, based on constrained runs.

Note that the requirement of keeping East Haven open represents a more costly constraint than not expanding at Wethersfield, particularly when the number of facilities is between ten and twelve. Also, with East Haven forced into the solution, adding the constraint of no expansion at Wethersfield does not present a serious additional loss in savings when there are ten or more facilities. Therefore, if the East Haven constraint is to be honored, it makes sense to simultaneously disallow expansion at Wethersfield, since the extra cost of this is not high. Based on the last column of Table 5, the solution which emerges as being worthy of further consideration is the eleven facility solution resulting in $ 3.09 million in savings. Going from twelve facilities to eleven when both constraints apply results in a marginal savings of $ 1.49 million, whereas going from eleven to ten only saves $ 0.89 million. Also, the EHAV/WETH, 10 solution has undesirable characteristics related to the closing of the Putnam facility. Therefore, based on the results of the constrained run set, the EHAV/WETH, 11 solution is highlighted for further investigation as part of the cost and demand sensitivity runs.

Cost Sensitivity Runs

To investigate sensitivity of results to changes in cost parameters, this set of runs was designed by varying transportation costs and overhead costs simultaneously. Expansion costs were kept at their normal levels throughout all runs. Table 6 shows the combinations of costs used for this run set. Note that the center cell of Table 6 uses the same cost levels as those used in the main set of runs.

For each cell, Table 6 summarizes the net present value of the savings offered by three solutions -- the optimal unrestricted solution, the optimal 10-facility solution, and the optimal constrained 11-facility solution. These savings are relative to the optimal 13-facility solution for that scenario. Also shown in each cell of the table are the percentages of possible savings captured by the 10-facility and 11-facility solutions.

Consider the results shown in the lower-right cell of Table 6. When overhead costs are decreased by 20 % and transportation costs increased by 20 %, the optimal solution has eight open facilities. The net present value of savings offered by this 8-facility solution (relative to the optimal 13-facility solution under the same cost assumptions) is $ 3.4 million. Under the given cost assumptions, a 10-facility solution offers $ 2.7 million in savings, which is 80 % of the savings offered by the 8-facility solution, and a constrained 11-facility solution offers $ 1.6 million in savings, which is 47 % of that offered by the 8-facility solution.

Table 6. Summary of cost sensitivity runs.

Overhead Costs	Transportation Costs: - 20 %	Transportation Costs: Normal	Transportation Costs: + 20 %
+ 20 %	6: \$ 11.8 10: \$ 7.0 (59 %) 11: \$ 4.6 (39 %)	6: \$ 10.1 10: \$ 6.5 (64 %) 11: \$ 4.2 (41 %)	7: \$ 8.9 10: \$ 6.0 (68 %) 11: \$ 3.7 (42 %)
Normal	7: \$ 8.3 10: \$ 5.3 (64 %) 11: \$ 3.5 (43 %)	7: \$ 7.1 10: \$ 4.8 (68 %) 11: \$ 3.1 (43 %)	7: \$ 5.9 10: \$ 4.4 (74 %) 11: \$ 2.6 (45 %)
- 20 %	7: \$ 5.3 10: \$ 3.7 (69 %) 11: \$ 2.5 (47 %)	8: \$ 4.2 10: \$ 3.2 (75 %) 11: \$ 2.0 (48 %)	8: \$ 3.4 10: \$ 2.7 (80 %) 11: \$ 1.6 (47 %)

(Dollar values are savings relative to optimal 13-facility solutions. These are net present values, in millions of dollars. For each 10 and 11 facility solution, the percentage of possible savings is also shown).

Now consider the results for the upper-left cell of Table 6. With high overhead costs and low transportation costs, the optimal solution contains only six open facilities. Compared to the optimal 13-facility solution under these conditions, the 6-facility configuration saves \$ 11.8 million; a 10-facility solution saves \$ 7.0 million, and a constrained 11-facility solution saves \$ 4.6 million. For the ten and eleven facility solutions, the savings are 59 % and 39 %, respectively, of the savings offered by the 6-facility solution.

Figure 9 displays the savings offered by the optimal 10-facility solution under each scenario, and Figure 10 shows similar results for the constrained 11-facility solutions. These figures show that the savings achieved by closing facilities would be higher if overhead costs were higher, and lower if transportation costs were higher. However, the closing of facilities in both types of solutions provides significant benefits under all of the cost scenarios investigated.

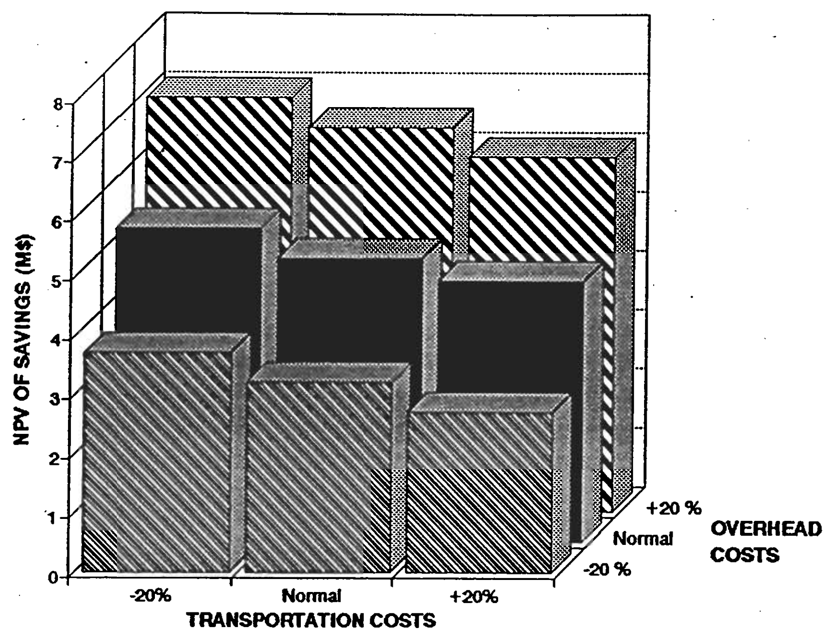


Figure 9. Savings offered by 10-facility solutions under different cost scenarios.

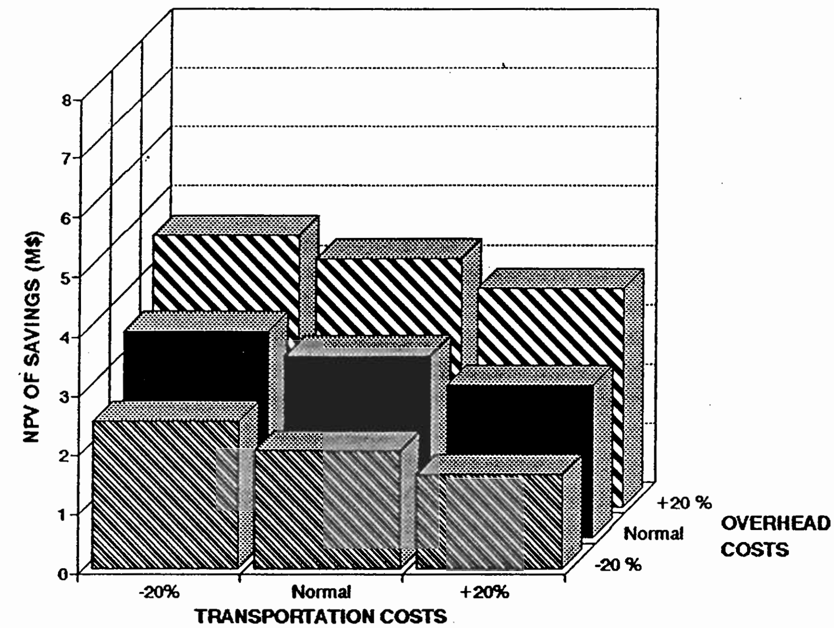


Figure 10. Savings offered by 11-facility solutions under different cost scenarios.

In Appendix G, solution summary pages are presented for the unrestricted, 10-facility, and constrained 11-facility solutions obtained for all cost sensitivity runs. This means that 24 summaries are presented, three for each cell of Table 6 except the center cell. It is not necessary to present solution summaries for the 13-facility solutions because they are all identical to the solution for the 13-facility case in the main experiment, except their total costs are different. The total cost associated with the 13-facility solution for each scenario in the cost sensitivity runs can be obtained from any solution summary page by adding the indicated savings to the optimal objective function value of the solution shown.

Demand Sensitivity Runs

Equipment repair requirements, which are the demands on the facilities, present another area for sensitivity analysis. There are several possible causes of changes in repair requirements. For one thing, changes in the severity of winters could change the level of demand. This is not a major concern because these changes are temporary, and the demand and capacity analysis performed in Appendix B is based on an existing system which has been in operation for many years, including several with severe winters. There are, however, other possible sources of more permanent demand level changes. One possible concern is an increase in repair requirements caused by the aging of equipment. If this occurs, we could expect more frequent visits (i.e. higher transportation costs) and higher levels of demand. Possible sources of decreased demands at the facilities are: 1) an increased use of subcontracting; and 2) increased repairs performed off-site, such as where the equipment is housed. To test the sensitivity of solutions to these kinds of changes, we have set up the demand sensitivity runs shown in Table 7. For each cell of this table, transportation costs and demand levels have been changed by the percentages indicated. Note that the center cell of the table corresponds to the scenario dealt with in the main run set. As with the cost sensitivity analysis, runs in each cell were done for unrestricted, 10-facility, constrained 11-facility, and 13-facility versions of the scenarios. Results are summarized in this table using the same format as Table 6.

Table 7. Summary of demand sensitivity runs.

5: $ 9.8	6: $ 8.2	7: $ 7.1	7: $ 5.9	8: $ 4.5
10: $ 5.9 (60 %)	10: $ 5.3 (65 %)	10: $ 4.8 (68 %)	10: $ 4.4 (75 %)	10: $ 3.8 (84 %)
11: $ 3.8 (39 %)	11: $ 3.5 (43 %)	11: $ 3.1 (43 %)	11: $ 2.7 (46 %)	11: $ 2.3 (51 %)
- 20 %	- 10 %	Normal	+ 10 %	+ 20 %

For each of the four cells where demand levels are changed, four solution summary pages are presented in Appendix G to further describe the unrestricted, 10-facility, constrained 11-facility, and 13-facility solutions.

V. RECOMMENDATIONS AND DISCUSSION

In this section, the recommended options are presented and discussed in detail. Also, a variety of concerns which are not considered by the optimization model are introduced and discussed, with particular emphasis on how they relate to the recommended options.

As mentioned in Section I, the two recommended options consist of ten and eleven repair facilities. The selection of ten and eleven facilities, as opposed to fewer, has been made by considering the results of the optimization model in conjunction with concerns that the model does not include. One such concern is the disruption that will occur when a facility is closed. One major disruption is the reassignment of mechanics from closed facilities to facilities with increased workloads. Appendix F helps to analyze reassignments, but nowhere in the optimization model are the costs of such reassignments considered. Other minor disruptions will also occur when facilities are closed. The existing system of thirteen facilities is well-established, with many system-specific managerial and operating procedures in place. Many adjustments will be required to implement closings, and each adjustment has its costs.

The ten and eleven facility systems appear to strike a good balance between cost savings and disruptions caused by changes; although the balance is obviously not the same for both options. Of the two, the ten facility option is more disruptive but higher in savings, while the eleven facility option is easier to implement and operate but provides less cost savings. In the runs of the optimization model presented in Section IV, the ten-facility system captured over 68 % of the costs savings offered by a seven-facility system relative to the optimal thirteen-facility system, while the constrained eleven facility system captured 43 %.

Considering the results shown in Table 6, the attractiveness of each option appears to be relatively insensitive to changes in cost parameters. Although optimal solutions have anywhere from six to eight open facilities, depending on cost structures, the ten facility option always captures at least 59 % of the available savings, and the eleven facility option at least 39 %. Note, however, that the magnitudes of savings for both options are quite sensitive to costs. For the ten facility option, the net present value of savings varies from $ 2.7 million in the lower-right cell of Table 6 to $ 7.0 million in the upper-left cell, and for the eleven facility option the savings range from $ 1.6 million to $ 4.6 million.

Turning to the results presented in Table 7, we see that the attractiveness of each of the options is also not seriously affected by changes in demand levels. Optimal unrestricted configurations vary from five to eight facilities, but the optimal ten facility solutions always capture at least 60 % of the possible savings, and the optimal constrained eleven facility solutions capture at least 39 %.

Although the sensitivity results show the ten facility solution to be robust, it should be noted that solutions do change from one scenario to the next. In all ten facility solutions, the same three facilities are closed (Brookfield, East Haven and Higganum), but under different conditions assignments of garages to facilities are different. Also, the degree of expansion is quite variable, especially when demand levels are changed. Nevertheless, the ten facility solutions display far fewer changes under different scenarios than do the optimal unrestricted solutions.

The constrained eleven facility solution is even more robust than the ten facility solution. Throughout the cost sensitivity analysis, the solution remained unchanged. Changes in eleven facility solutions did occur in the demand sensitivity analysis, but the changes were less than those exhibited by the ten facility solutions and much less than those seen in optimal unrestricted solutions.

Another consideration favoring the ten and eleven facility systems is that in both cases the closed facilities can be readily sold because they do not have maintenance garages with them on the same site. If facilities such as East Granby and Putnam are closed, then the State would have the empty space from those facilities sitting unused on sites with maintenance garages. This empty space could require maintenance not considered in the optimization model, which would reduce the attractiveness of closing those facilities.

Having presented a case for recommending ten and eleven facility systems in general, let us now discuss details of the specific options being recommended.

Ten Facility Option

The solution summary page that follows presents the recommended ten facility option and the savings that it offers relative to the existing system.

As discussed in Section I, the existing system consists of thirteen facilities with garages assigned to them as indicated by the straight lines in the diagrams. Based on the cost parameters of the optimization model, the existing system has a total annual cost of $ 4,178,000, with $ 2,903,000 in annual overhead costs and $ 1,275,000 in annual transportation costs.

SOLUTION SUMMARY PAGE   Run title: 10 facility option

Scenario

Overhead costs: Normal   Transportation costs: Normal

Demand level: Normal   # of facilities: 10

Solution

Facilities closed: Brookfield, East Haven, Higganum

Facilities expanded: Waterbury, Wethersfield
(# of bays added)   (+4)   (+5)

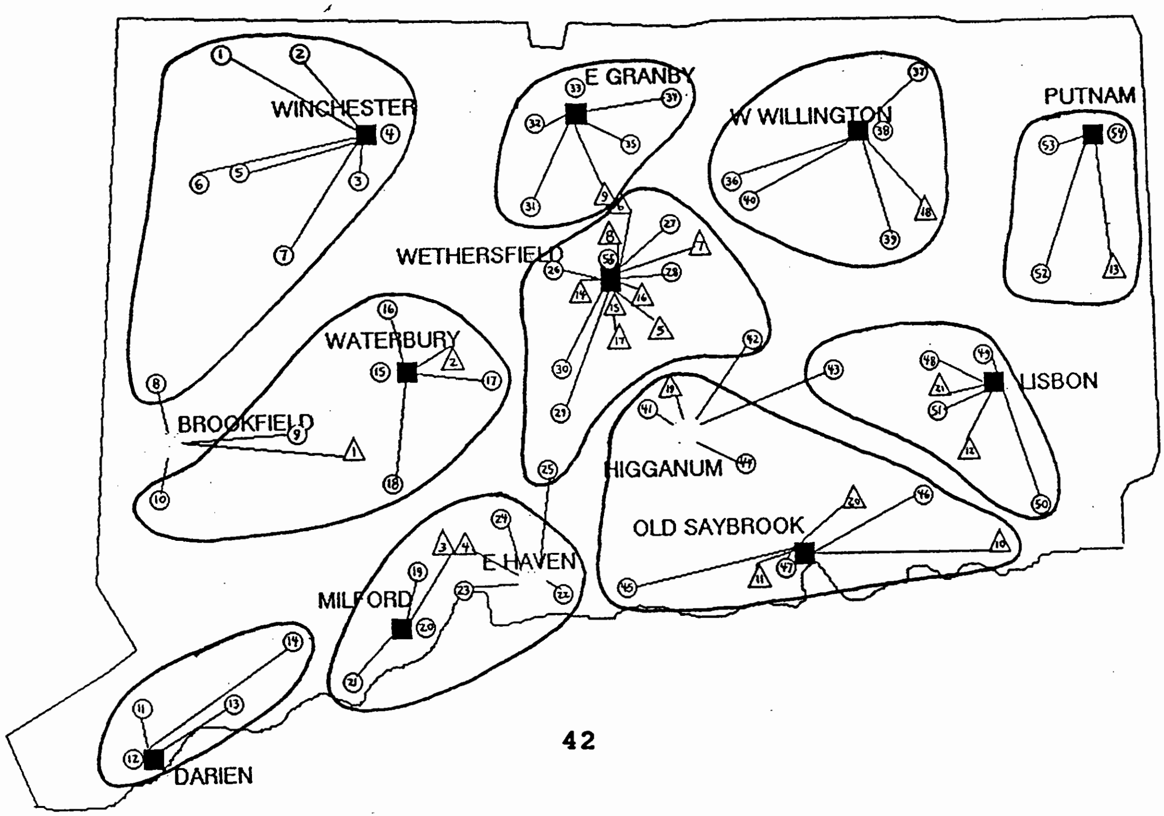
Total annualized cost (in thousands of dollars): 3700.00

Annualized cost components relative to existing 13-facility system (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-795.5	+233.1	+84.7	-477.7

Net present value of savings: $ 5.0 million

Savings compared to those offered by optimal, unrestricted solution: 65 %



The solution summary page shows the cost of the ten facility option relative to the existing system, and it breaks cost changes down into overhead, transportation and expansion components. The net present value of the total savings is $ 5.0 million, based on a 20 year horizon and an interest rate of 7.125 %. Table 8 summarizes the savings offered by the recommended solution, and Table 9 further explains the savings by breaking it into components. These components are detailed even further in Appendices A and C, where the costs parameters are developed.

Table 8. Summary of Annualized Savings (in millions of dollars) for the ten facility option.

	Overhead	Transportation	Expansion	Total
Existing System	2.903	1.275	0	4.178
Recommended System	2.107	1.508	.085	3.700
Difference:	- .796	+ .233	+ .085	- .478

Table 9. Breakdown of savings for the ten facility option into annual and one-time components.

		Annual	One-Time
Overhead Costs:	Brookfield:	- 158,100	- 1,293,000
	East Haven:	- 178,600	- 1,121,000
	Higganum:	- 163,500	- 683,000
Expansion Costs:	Waterbury:	+ 14,360	+ 251,100
	Wethersfield:	+ 17,955	+ 298,100
Additional Transportation Costs:		+ 233,100	
	Totals:	- 234,785	- 2,547,800
		x 10.49*	
	Net Present Values:	- 2,462,900	- 2,547,800

Combined Net Present Value: - $ 5,010,700

(* This factor reflects a 20-year horizon and a 7.125 % interest rate.)

The additional transportation costs shown in Table 9 are listed as annual costs, but in Appendix C the transportation costs were developed by considering both operating costs and costs of capital equipment. To implement the recommended solution, some of the transportation costs may need to be paid up-front as lump-sum costs for new equipment. In particular, a new low-bed trailer might be needed, at a cost of approximately $ 116,000. This new trailer would be used to handle increased requirements for transport of heavy motorized (category 3) equipment.

With the closings of Brookfield, East Haven, and Higganum, garages 8, 10, 22, 24, 41, 44, OTH4 and OTH19 all change from being within 10 miles of repair facilities to being beyond 10 miles. Under our assumptions, this means that their category 3 equipment will now require low-bed trailer transport, whereas before much of it could be driven in for repair. Combined, these garages have a total of 86 pieces of category 3 equipment, which each require an average of 3.4 trips per year for repair. Thus, an estimated total of 292 new low-bed trailer trips would be needed each year, which could necessitate the purchase of a new low-bed trailer. Capital equipment costs are included in the category 3 equipment's annual transportation costs, so the increase in transportation costs shown in Table 9 does allow for capital expenditures. If a new low-bed must be purchased, then the transportation costs in Table 9 could be rewritten without changing the totals by showing a one-time cost of $ 116,000 and a reduced annual cost of $ 222,042.

Besides the cost aspects of the recommended system, it is also important to look at certain issues related to capacity. One key capacity issue is the expansions being recommended at the Waterbury and Wethersfield sites. It should be noted that the feasibility of the expansions at both Waterbury and Wethersfield need to be verified. Our visits to the sites and study of site plans lead us to believe that there is room for the recommended expansions, but more detailed studies should be made.

The recommended expansion at Waterbury is 4 bays, which was obtained by rounding up the 3.5 bays indicated in the Main, 10 solution shown in Appendix G. This expansion is needed to accommodate the increased requirements picked up by Waterbury as a result of closing Brookfield.

For Wethersfield, our recommendation is for a 5 bay expansion, which is 3 bays less than the expansion indicated in the Main, 10 solution. Two differences between the Main, 10 solution and our recommended solution allow for the reduction in the number of bays added at Wethersfield. The most significant difference is that our recommendation includes a greater role for the Old Saybrook facility than does the Main, 10 solution. Specifically, garage 41 and OTH19 are served by Old Saybrook in our recommendation, as opposed to Wethersfield which serves them in the Main, 10 solution. These changes increase transportation costs, but they allow for a lesser expansion at Wethersfield and a better use of existing capacity at Old Saybrook. Note that in the cost sensitivity experiments, an expanded role for Old Saybrook showed up in 10-facility solutions when transportation costs were reduced by 20 %.

The other change that allows a decreased expansion at Wethersfield is the assignment of OTH9 to East Granby instead of Wethersfield. This change is justified by the fact that East Granby serves OTH9 in the current configuration, so the change provides the benefit of less disruption while also allowing for a smaller expansion at Wethersfield.

The only other difference between the recommended solution and that in Main, 10 relative to Wethersfield is that the whole of garage 25 is assigned to Wethersfield in our recommendation, as opposed to the partial assignment indicated in Main, 10.

The net result of these changes is that transportation costs go up, while expansion requirements go down. We believe that the additional transportation costs are an acceptable price to pay for a solution that is less disruptive in terms of new construction and changes in assignments. Also, the expanded role for Old Saybrook is desirable because it is a new facility with a good amount of capacity, as shown in Appendix B.

Similar arguments to those given above can be used to justify the recommended assignments of garage 52 and OTH13 to Putnam, and the assignment of OTH10 to Old Saybrook. These are the only other differences between the recommended solution and that shown in Main, 10.

In the solution summary page for the recommended ten facility option, a savings with a net present value of $ 5.0 million is shown, and this is the amount that was broken down in Tables 8 and 9. It should be emphasized that this savings is relative to the existing system. In the analysis in Section IV, results were compared against optimal 13-facility solutions, which is why the net present value of the savings for the Main, 10 solution appears to be less than that of the recommended solution. As mentioned in Section IV, under our normal cost assumptions, the optimal

13-facility solution has a total annual cost which is about $ 58,800 less than that of ConnDOT's existing 13-facility system.

In the solution summary page for the recommended ten facility option, the entry for the percentage of savings is also on a different basis than in previous solution summaries. For the recommended solution it represents a percentage of the savings achieved by the Main, unrestricted solution over the existing system; whereas in the Main, 10 solution it represents a percentage of the savings achieved by the Main, unrestricted solution over the optimal 13-facility solution. In our view, the relevant basis for comparison changes depending upon whether we are considering the advantages of closing facilities (as in Section IV), or whether we are presenting the benefits of a recommended configuration (as in this section).

Another aspect of the recommended system to be analyzed is capacity utilization. Table 10 shows the number of bays at each facility in the ten facility option, and how much each facility can handle in terms of the measure developed in Appendix B. The table also shows the actual loads on the facilities, and the extra capacity, both in terms of equipment serviceable and numbers of work bays.

Table 10. Capacity and loads served in the recommended ten facility option.

				Extra Capacity	
Facility	# of bays	equipment serviceable	load	equipment serviceable	# of bays
Putnam	12	110.04	53.88	56.16	5.4
Lisbon	13	120.48	92.70	27.78	2.7
W.Willington	11	99.60	77.14	22.46	2.2
O. Saybrook	14	130.92	116.54	14.40	1.4
Milford	15	141.36	136.29	5.07	0.5
Darien	15	141.36	67.44	73.92	7.1
Winchester	13	120.48	104.74	15.74	1.5
Waterbury	13	120.48	115.21	5.27	0.5
E. Granby	13	120.48	84.19	36.29	3.4
Wethersfield	23*	224.88	218.72	6.16	0.6
	142				25.3

(* The number of bays for Wethersfield has been adjusted upward by one to reflect that site's current practice of off-loading some work to Putnam)

One thing to notice about the ten facility option is that the total number of work bays (142) is 26 bays less than the existing system, which has 168 bays, as shown in Appendix B. Even with this reduction, however, the recommended system still has a total of 25.3 bays worth of extra capacity, as indicated in the last column of Table 10. Thus, the ten facility option cuts the extra capacity of the repair system by approximately half. As one might expect, a similar type of analysis using the seven-facility solution from the Main, unrestricted run would show that implementation of that solution would involve the elimination of practically all excess capacity. While the complete elimination of excess capacity might seem like a desirable goal, it should be noted that some of this excess could prove to be quite useful in times of severe weather or other situations that cause increased requirements.

Not only is the total excess capacity of the system important, but so is its distribution. One favorable aspect of the ten facility option is that all facilities have at least a half bay's worth of extra capacity -- none of them is pushed to its absolute limit. Also, for those with the least amount of extra capacity (i.e. Milford and Waterbury), there is a facility nearby with considerable extra capacity (i.e. Darien), which could help during conditions of extraordinarily high demand. Putnam is another facility with a good deal of extra capacity, which is used in the current system by sending some equipment from Wethersfield to Putnam when Wethersfield is overburdened. This could also be done in the recommended ten facility option.

Eleven Facility Option

The solution summary page that follows presents the recommended eleven facility option and the savings that it offers relative to the existing system. Tables 11 and 12 further describe the savings in the same format used in Tables 8 and 9.

SOLUTION SUMMARY PAGE   Run title: 11 facility option

Scenario

Overhead costs: Normal   Transportation costs: Normal

Demand level: Normal   # of facilities: 11

Solution

Facilities closed: Brookfield, Higganum

Facilities expanded: None
(# of bays added)

Total annualized cost (in thousands of dollars): 3880.17

Annualized cost components relative to existing 13-facility system (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-510.0	+212.5		-297.5

Net present value of savings: $ 3.1 million

Savings compared to those offered
by optimal, unrestricted solution: 40 %

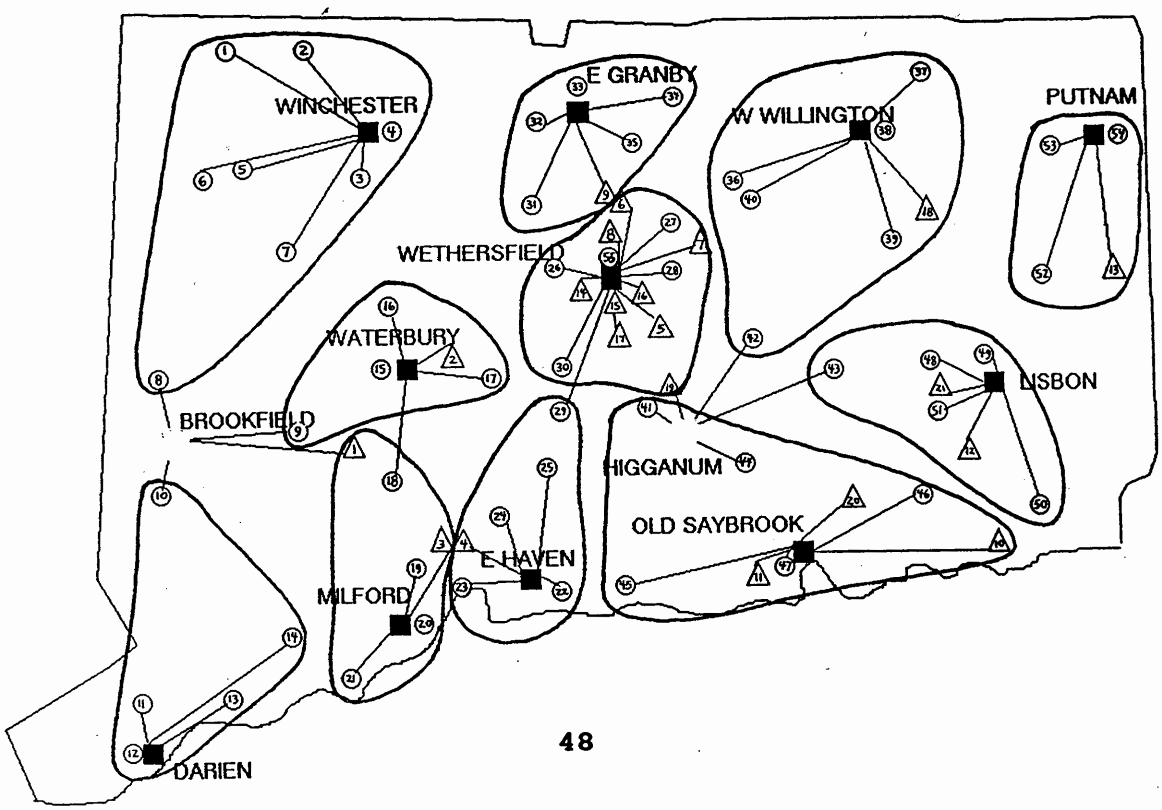


Table 11. Summary of Annualized Savings (in millions of dollars) for the eleven facility option.

	Overhead	Transportation	Expansion	Total
Existing System	2.903	1.275	0	4.178
Recommended System	2.393	1.487	0	3.880
Difference:	- .510	+ .212	0	- .298

Table 12. Breakdown of savings for the eleven facility option into annual and one-time components.

		Annual	One-Time
Overhead Costs:	Brookfield:	- 158,100	- 1,293,000
	Higganum:	- 163,500	- 683,000
Additional Transportation Costs:		+ 212,500	
	Totals:	- 109,100	- 1,976,000
		x 10.49*	

Net Present Values:		- 1,144,500	- 1,976,000

Combined Net Present Value: - $ 3,120,500

(* This factor reflects a 20-year horizon and a 7.125 % interest rate.)

As with the ten facility option, the additional annual transportation costs for the eleven facility option shown in Table 12 could be adjusted downward to $ 201,442 to reflect a lump-sum cost of $ 116,000 for a new low-bed trailer. With the eleven facility option, the following garages are no longer within 10 miles of repair facilities: GAR8, GAR10, GAR41, GAR44 and OTH19. These represent fewer changes than those in the ten facility option, but the purchase of a new low-bed trailer may still be required.

There are several differences between the recommended eleven facility option and the solution obtained from the optimization model, which is the one shown on the solution summary page labeled EHAV/WETH, 11 in Appendix G. Most of the differences are due to a preference for distributing excess capacity and maintaining current assignments. Garages 10 and 14 are assigned to Darien in the recommended system so as to better utilized the capacity of that facility. Similar reasoning was used in keeping the assignments of GAR45 and OTH10 at Old Saybrook and GAR52 and OTH13 at Putnam.

For East Granby, keeping the current assignment of OTH9 to that repair facility enables OTH6 and GAR26 to remain with Wethersfield. Sending all of GAR42 to West Willington also helps to allow GAR26 to stay at Wethersfield in the recommended configuration.

Other differences between the optimal solution and the recommended one exist in the areas of Waterbury, Milford, and East Haven. These changes are also intended to minimize the disruptive impact of changed assignments, and to balance excess capacity across facilities.

To characterize capacity utilization in the recommended eleven facility option, Table 13 shows equipment serviceable and actual loads served for all of the open facilities. Note that each facility in the system has at least 0.6 bays worth of excess capacity. Compared with the ten facility option, the eleven facility system has more extra capacity at Old Saybrook and Milford, and less at West Willington and Darien. Overall, the eleven facility option has about three bays more of extra capacity than does the ten facility option. Compared with the existing system, the eleven facility option, with 146 bays total, represents a net reduction of 22 bays.

Given the lesser savings of the eleven facility option relative to those offered by the ten facility option, possible reasons for choosing the eleven facility option should be discussed. The advantages of the eleven facility option are due to its relative ease of implementation and operation. With regard to implementation, the main advantages of the eleven facility system are: 1) no new construction; and 2) fewer workforce changes.

With no new construction in the eleven facility option, the closings at Brookfield and Higganum could be implemented immediately. Although the repair facility at Darien may be still under construction, our analysis shows that the existing facility at Norwalk would have sufficient capacity to handle garage 10 as long as mechanics are reassigned appropriately. Because the eleven facility option can be implemented immediately, the associated cost savings can be achieved right away. This could be a big advantage, considering the immediate pressure for the State to cut costs.

Table 13. Capacity and loads served in the recommended eleven facility option.

Facility	# of bays	equipment serviceable	load	Extra Capacity: equipment serviceable	Extra Capacity: # of bays
East Haven	13	120.48	98.64	21.84	2.1
Putnam	12	110.04	53.88	56.16	5.4
Lisbon	13	120.48	92.70	27.78	2.7
W.Willington	11	99.60	90.28	9.32	0.9
O. Saybrook	14	130.92	107.68	23.24	2.2
Milford	15	141.36	107.58	33.78	3.2
Darien	15	141.36	83.60	57.76	5.5
Winchester	13	120.48	104.74	15.74	1.5
Waterbury	9	78.72	71.66	7.06	0.7
E. Granby	13	120.48	84.19	36.29	3.4
Wethersfield	18*	172.68	166.43	6.25	0.6
	146				28.2

(* The number of bays for Wethersfield has been adjusted upward by one to reflect that site's current practice of off-loading some work to Putnam)

The other implementation advantage mentioned for the eleven facility system relates to workforce changes. With two facilities closing instead of three, the impact on the workforce will be less severe in terms of both layoffs and reassignments. Recommended reassignments of mechanics for both of the recommended options are presented in Appendix F.

Switching from implementation concerns to operation issues, several additional advantages of the eleven facility option can be described. The justification for performing the constrained runs described in Section IV is that ConnDOT maintenance management feels that East Haven is a key facility for several reasons. For one thing, the facility is located near the busy I-91 / I-95 intersection, an area where effective roadway maintenance is crucial. Maintenance management feels that it is advantageous to have a repair facility near this area, particularly during critical situations such as snowstorms. The other factor in favor of keeping the East Haven facility is that it is one of the best designed facilities in the State. With a drive-though lane down its center, equipment can be easily towed in for repair. Other advantages of the facility's design cited by maintenance management are: 1) easier supervision of mechanics; and 2) improved energy efficiency.

Besides keeping East Haven open, the eleven facility system also offers the advantages of not increasing the load at Wethersfield and not causing a major increase at Milford. Maintenance management has expressed concerns about the increased loads to both of these sites in the ten facility option.

The constraints that were introduced in the constrained run set in Section IV are "soft" in that they prevent undesirable features rather than preventing physical impossibilities. Since it is these constraints upon which the eleven facility option is based, their validity is a major focus in the decision of whether the eleven facility option should be preferred to the ten facility option. Are the desirable features of keeping East Haven open and not having expansions at Wethersfield worth a decrease in savings of $ 1.89 million? In choosing between the two recommended options, this is one of the questions that must be considered by those who represent the interests of the State.

Other factors should also be considered when deciding which option is best for <u>right now</u>. In support of the eleven facility option is the argument that the selection of a particular option does not preclude further changes to the maintenance system in the future. Because of the differences between the two systems, we would not recommend implementation of the eleven facility option as an interim measure prior to the construction of new bays for the ten facility option. However, we do recommend that the maintenance system be further studied to identify additional areas for savings. In particular, a broader analysis which includes the locations of the seventy six maintenance garages and other facilities where equipment is housed could yield recommendations which offer higher long-run savings than those identified in the current study. Considering this, the eleven facility option has an advantage over the ten facility option in that it does not commit to construction of any new work bays. For ten facility solutions, the degree of expansion was seen to be variable in the cost and demand sensitivity analyses. Therefore, these is reason to believe that changes to the system along the lines of those not considered in the current study (e.g. increased use of subcontracting and/or relocation of maintenance garages) would change the expansions indicated in the ten facility option. Considering that new construction has a relatively long lead time and involves up-front expenditures, it makes sense to avoid expansions if other changes to the maintenance system are likely to be recommended based on continued study.

General Issues

One issue to discuss pertaining to both of the recommended options is one which is not completely considered in the optimization model -- i.e. the fact that the Higganum site houses a test boring area which occupies several bays worth of space for storage of core samples and equipment. We have assumed that this area would be relocated if the Higganum repair facility were closed. Costs were included in the optimization model to reflect building expenses and moving costs, but new construction costs were not included. ConnDOT management has indicated that the test boring area can be accommodated by the new maintenance garage at East Haddam. If there are costs associated with altering construction at East Haddam to handle the test boring area, then these should be subtracted from the savings indicated for closing the facility at Higganum, since the optimization model did not include any such costs.

Part of the one-time benefits for closing Higganum which are included in the optimization model is savings of $ 161,000 in future repairs that would not be required if the site were closed. Of all the existing repair facilities (excluding West Willington and Norwalk which are being replaced), Higganum is clearly the most out of date. Furthermore, height restrictions on bays at Higganum require that some equipment assigned to the facility go to Old Saybrook for repair. These considerations lend further support to the closing of the Higganum facility, even though the relocation of the test boring area would be required.

Perhaps the most negative effect of closing repair facilities is that certain garages will be required to send their equipment greater distances for repair. Of all the garages reassigned in the recommended options, New Milford (garage 8) is the most seriously affected. Instead of travelling for about 9 minutes one-way to Brookfield, in both of the recommended options equipment would need to travel for about 46 minutes to get to Winchester. With an estimated total of 225 trips per year between New Milford and its repair facility, it is clear that there will be extra work involved for the workers and equipment at the garage.

Of course, the costs of the extra work have been considered in the optimization model, where a conservative approach was taken by assuming that all equipment transport is done on an overtime basis. Indeed, if either of the recommended options were adopted, an increase in the use of overtime at New Milford should be expected. However, a number of sound management techniques could be used to reduce the impact of the increased travel distance. Coordination of trips is one obvious technique -- i.e. picking up a completed truck when dropping another off for repair so that another worker does not need to follow in a separate vehicle. Although costs and workloads will increase at some garages, these negative effects are more than offset by the system-wide savings offered by the recommended options.

At this point, let us address concerns regarding the impact of changes on service levels. The demand and capacity analysis in Appendix B was structured such that some of the existing facilities served as benchmarks for defining the capacities of other facilities. With our recommendations based on this type of analysis, we have a high degree of certainty that enough work bays will be available to serve the equipment assigned to a facility. Also, the reassignment of mechanics suggested in Appendix F addresses the issue of having the correct number of mechanics to handle the repairs. Since both work bays and mechanics are considered, the repair facilities in the recommended options will have the capacity to provide the same level of service as the existing system.

Although repair capacity will be sufficient, there is also a concern about congestion at some sites due to increased loads being served. For example, in the recommended ten facility option Milford experiences a significant increase in equipment served. ConnDOT maintenance management has expressed a concern that parking space at Milford may be insufficient to handle an increased number of vehicles. While this is a legitimate concern, we believe there are ways in which this type of issue can be resolved. The arrival process of vehicles for repair need not be completely random. Large numbers of vehicles awaiting repair can be avoided by implementing relatively simple scheduling rules. This is an example of how maintenance management could refine certain practices to enable a leaner system to operate effectively. Given sufficient capacity in terms of work bays and mechanics, other factors such as limited parking space should be manageable.

Even with the effective management of operations at repair sites, there is still concern about the impact of increased transportation requirements at garages such as New Milford. The question arises: "Won't these increased transportation requirements decrease the productive time of the equipment and workers?" This is an important question, and a number of points are relevant for addressing it.

First, as already mentioned, we have allowed for all transport to be done on an overtime basis at time-and-a-half wages. Therefore, as long as there are employees willing to work overtime to transport equipment to repair facilities, there should be no negative impact on equipment and worker availability.

Overtime labor may not be the best way to accommodate increased transportation requirements, even though it was used as part of the basis for estimating costs. Instead of planning to use the amount indicated by the model for overtime labor, other uses of the funds could be considered. For example, the annual amount allowed by the model for transportation from New Milford (garage 8) to Winchester is $ 76,670 (see page D.16). By contrast, the cost of the New Milford to Brookfield assignment is only $ 14,210 per year. This means that the model is allowing over $ 60,000 per year to handle the increased transportation requirements for New Milford. With this amount available, many possibilities exist for accommodating the increased requirements while minimizing the impact on equipment and labor availability. Ideas on how to best handle the increased workload while staying within the budgeted amount could be solicited from the maintenance workers at the New Milford garage. The use of overtime labor is just one alternative, and it might not be the most attractive.

Regarding equipment availability, it should be noted that equipment transport time is currently a relatively small portion of total equipment down time. Table 14 shows the average amount of time that equipment in each category is unavailable per repair visit. This information was obtained by sampling the historical records contained in the PM PLANNER software used for the data collection discussed in Appendix B. For each category, data from 100 randomly selected pieces were collected. The down time figures may be overstated because PM PLANNER does not subtract off weekends or holidays. Also, data were collected over a period when budget constraints caused problems with spare part availability, resulting in higher than normal down times. Nevertheless, Table 14 indicates that down times per visit are on the order of days. Considering that the total round-trip transportation time is always well under two hours in the recommended system, it is clear that, percentagewise, additional transportation time will not be a major source of equipment down-time. Sound management of maintenance scheduling and equipment transport could more than offset the impact that additional travel distances would have on equipment availability.

Table 14. Average equipment down time per repair visit.

Equipment Category:	1A	1B	2	3	4	5
Average down time per visit: (in days)	4.7	2.9	3.9	6.1	6.0	8.4
Standard error of estimates: (in days)	0.5	0.5	0.6	1.3	2.2	4.2

Implementation of the recommended changes in either option will be a challenge for maintenance management. There is bound to be resistance by employees at affected garages and repair facilities. Resistance to change is a natural reaction which ConnDOT management should anticipate and plan for. If affected workers are given a chance to provide their inputs at early stages of the implementation process, then the chances for a smooth transition to a new system will be greatly improved.

A final implementation issue that needs to be discussed is one related to the sale of closed facilities. Estimates obtained for the property values of the sites did not consider that some site clean-up may be necessary prior to sale. Depending on the intended use of the site by a prospective buyer, the State might need to spend more for environmental clean-up at the site then it would if the site were to be continued as a repair facility. Cost estimates for clean-ups needed at Brookfield, East Haven and Higganum were not readily available for this study. However, because clean-ups can be expensive, this issue should not be ignored. When analyzing clean-up costs, the relevant amount to subtract from the savings associated with the sale of a site is the <u>difference</u> between what it would cost to prepare it for sale versus what it would otherwise cost to clean up. It would be inappropriate to simply subtract the total cost of a clean-up from projected revenues because clean-ups need to be done for environmental reasons, regardless of whether or not a site is to be sold.

With regard to the existing and recommended systems, the question might be asked, "How does Connecticut practice compare with that of other states?" While such a comparison is quite difficult because of varying degrees of responsibility, operating conditions, and policies, we felt it might be helpful as long as the limitations of the comparison are kept in mind. To this end, a survey of all of the states and the Canadian provinces was conducted. Thirty three states and seven provinces responded. Of these, eighteen having maintenance systems similar to ConnDOT were selected for analysis. Based on these analyses, it appears that, for the size of the State, ConnDOT maintains a relatively high number of pieces of equipment, and it services that equipment in a relatively high number of garages. Details of survey results and analyses are presented in Appendix E.

Besides surveying other transportation departments as part of this study, the principal investigators also visited: 1) a private firm that maintains their own fleet of heavy equipment; and 2) the large Hartford facility where Connecticut Transit maintains buses.

The private operation visited is Tilcon Tomasso's facility in New Britain. Tilcon has four repair facilities in Connecticut, each located near a quarry. New Britain is their largest repair facility, with 9 work bays and 29 mechanics operating over two shifts. The most striking difference between the repair operations of Tilcon and ConnDOT is that Tilcon has a much lower work bay per mechanic ratio. Dividing Tilcon's number of mechanics by two to account for the two shifts, their ratio at New Britain is .62 bays per mechanic. As discussed in Appendix F, the repair facilities in ConnDOT's existing configuration have an average of 1.31 bays per mechanic, and the ratios are 1.11 and 1.14 in the recommended options.

Our contact at Tilcon acknowledged that conditions at New Britain are sometimes crowded. He said it is not uncommon to have mechanics working outside when all bays are occupied. The advantage of a lower bays per mechanic ratio is lower overhead costs, and one of the reasons that Tilcon is able to achieve this benefit is because their peak repair requirements occur during fair weather. Because ConnDOT's peak demands occur during snowstorms and cold weather, it is not reasonable to expect outside areas to be used as extra space for performing repairs. Nevertheless, the Tilcon facility can still be used as a point of reference, as long as the limitations of the comparison are acknowledged. Comparing ConnDOT to Tilcon tends to confirm that the reductions in bays associated with the closings in the recommended options do not result in drastically low bays per mechanic ratios. Other comparisons between Tilcon and ConnDOT were not pursued because the large differences between the systems make direct comparisons difficult.

In addition to Tilcon Tomasso, the Connecticut Transit facility in Hartford was also visited. This large facility services 240 buses that operate in the Hartford area. The facility also performs some of the major rebuilding repairs for buses from New Haven and Stamford. Other repairs for those two areas are performed at separate facilities located near the cities.

The Hartford facility has approximately 64 mechanics who operate over three shifts. Major repairs are performed only on the first shift, with the other two shifts performing relatively minor repairs to keep the buses running. In a sense, maintaining the buses is an easier problem than that faced by ConnDOT's equipment repair system because all of the buses are essentially the same. The Connecticut Transit mechanics are trained specifically for bus maintenance, and much of the repair and diagnostic equipment at the facility is specialized. Connecticut Transit has made impressive progress recently in their training methods, and ConnDOT might be able to transfer some of those gains to their equipment repair system. However, the fact that ConnDOT mechanics must perform repairs on a wider variety of equipment makes their training requirements more complex. The dispersion of the ConnDOT equipment and the fact that it is generally not maintained where it is housed are two other differences between the ConnDOT and the Connecticut Transit systems.

The use of more than one shift at both Tilcon and Connecticut Transit brings up the issue of whether extra shifts at repair facilities might be useful in the ConnDOT system. To examine this issue in the context of the optimization model, several assumptions pertaining to the extra shift must be made. In developing the assumptions, Mr. James E. Lewis, Jr., Equipment Repair Supervisor was our primary source of information.

One key assumption regarding a second shift relates to the personnel required to support the mechanics' activities. We assume that the level of support staff for a second shift would be the same as for the first, except that a store supervisor would not be required. This means that a repair supervisor, a crew leader, a secretary, and a store clerk would all be needed for the second shift. Because the salaries of the repair supervisor and secretary were included in the overhead savings associated with closing a facility, their salaries must be added to the overhead costs associated with using a second shift. Also, a shift pay premium of $ .65/hour for each of these workers must also be included. Shift premiums for the crew leader and store clerk are also added in, but their base salaries are not because they were not included in the overhead savings associated with closing a facility, since we assumed crew leaders and store clerks would be transferred.

The cost of the labor overhead indicated above totals approximately $ 88,000/year. Additional overhead must be added to this to reflect added building expenses incurred by operating an extra shift. Mr. George Conkling, Jr., Director of Property Control estimates that energy-related building expenses can be expected to rise by 1/3 to 1/2 if an extra shift is added on a permanent basis. Using the midpoint of this range, the Wethersfield facility would be expected to have increased building expenses of about $ 27,200 per year if a second shift were added. This raises the total annual overhead costs of adding an extra shift to $ 115,200. Note that labor expenses account for over 75% of the second shift overhead, even for Wethersfield, which has the highest building expenses.

Besides the overhead expenses, we must also consider the cost of mechanics on the second shift. Mechanics' pay was not considered previously because we had always assumed that mechanics would be transferred from closed facilities, so the total number of mechanics and their cost would remain constant. This assumption does not hold under the second shift scenario for two reasons. First, as already mentioned, second shift workers receive a pay premium of $ .65/hour. Second, for several reasons the second shift mechanics are expected to be less productive than those on the first shift.

The lower productivity of second shift mechanics is caused primarily by communication requirements associated with different mechanics working on the same equipment on different shifts. When a facility operates with only one shift, a mechanic can leave in the evening in the middle of a repair job and then continue the job the next morning without spending much time to identify where he left off. With a two shift operation, much time must be spent on communication between shifts. Even with communication, the mechanics must still spend time verifying the status of a job and determining what steps need to be performed next. The need for this coordination, particularly for intricate repair work, will effectively lower the amount of additional equipment that could be serviced by adding a second shift.

Considering the communication requirements, we cannot expect a second shift to double the amount of equipment serviceable by a facility. Besides the communication requirements, we must also consider that equipment occupying bay space while waiting for a replacement part will not have its repair time shortened very much by the existence of a second shift of mechanics. Everything considered, Mr. James

E. Lewis, Jr. estimates that an extra shift would allow a facility to service from 60 to 65 % more equipment than a single shift operation, assuming the same number of mechanics on both shifts. For our purposes, we assume an 80% level of second shift productivity so that we can base our analysis on an optimistic, best-case assumption.

Based on the 80% productivity estimate, Table 15 shows the number of second shift mechanics needed for various levels of increased equipment serviceable by a facility. The annual costs of these added mechanics is also shown in the table, along with the total annual cost of each option, which includes the overhead costs discussed previously.

The levels of added equipment serviceable shown in Table 15 were selected because they correspond to additions associated with adding various numbers of bays to facilities, as discussed in Appendices A and B. Table 16 shows information related to adding bays to achieve the same levels of increased equipment serviceable shown in Table 15. Note that the added equipment serviceable values shown in Tables 15 and 16 consider all equipment categories, so they are higher than would be indicated by the R and S parameters from Appendix B, just as the D_i' values shown in Table F.1 are higher than the D_i values given in Table B.2. The number of mechanics needed to achieve each level of increase shown in Table 16 is lower than the value in Table 15 because the values in Table 15 are based on the 80 % productivity factor for second shift mechanics.

Table 15. Costs of expanding capacity with a second shift.

Added Equipment Serviceable	# of Mechanics Added	Annual Mechanics' Labor Costs	Total Annual Costs
26.51	3.04	134,100	249,300
53.02	6.08	268,200	383,400
79.53	9.12	402,300	517,500
106.04	12.16	536,400	651,600
132.55	15.20	670,500	785,700

Notes: column 2 = column 1 / (10.91 x .80)
column 3 = column 2 x $ 44,109
column 4 = column 3 + $ 115,200.

Table 16. Costs of expanding capacity by adding bays.

Added Equipment Serviceable (and # of bays)	# of Mechanics Added	Annual Mechanics' Labor Costs	Total Annual Costs
26.51 (2)	2.43	103,000	125,150
53.02 (4)	4.86	206,000	244,300
79.53 (6)	7.29	309,000	363,450
106.04 (8)	9.72	412,000	482,600
132.55 (10)	12.15	515,000	601,750

Notes: column 2 = column 1 / (10.91)
column 3 = column 2 x $ 42,387
column 4 = column 3 + annual expansion costs

Adding annual labor costs to annualized expansion costs in Table 16, we obtain the total annual cost for each level of expansion. These total costs can be compared directly to those given in Table 15. Figure 11 graphically shows that at each level of added equipment serviceable, the cost of adding bays to a facility is much less than the cost of operating a second shift. The high overhead costs associated with the support personnel on the second shift combined with the lower mechanics' productivity result in the second shift being a relatively unattractive alternative.

The optimization model was supplemented to allow second shift operations, based on the costs indicated above. As expected, second shifts at the facilities were not included in an optimal solution. This supports the conclusion that the use of extra shifts is not a good alternative for normal repair facility operations.

Extra shifts at repair facilities are currently used to add repair capacity during snow storms. The use of a second shift for normal operations would have the undesirable effect of reducing the amount of extra capacity available during snowstorms. The need to reschedule mechanics is another point against the second shift, assuming that mechanics would generally prefer to continue working their normal hours.

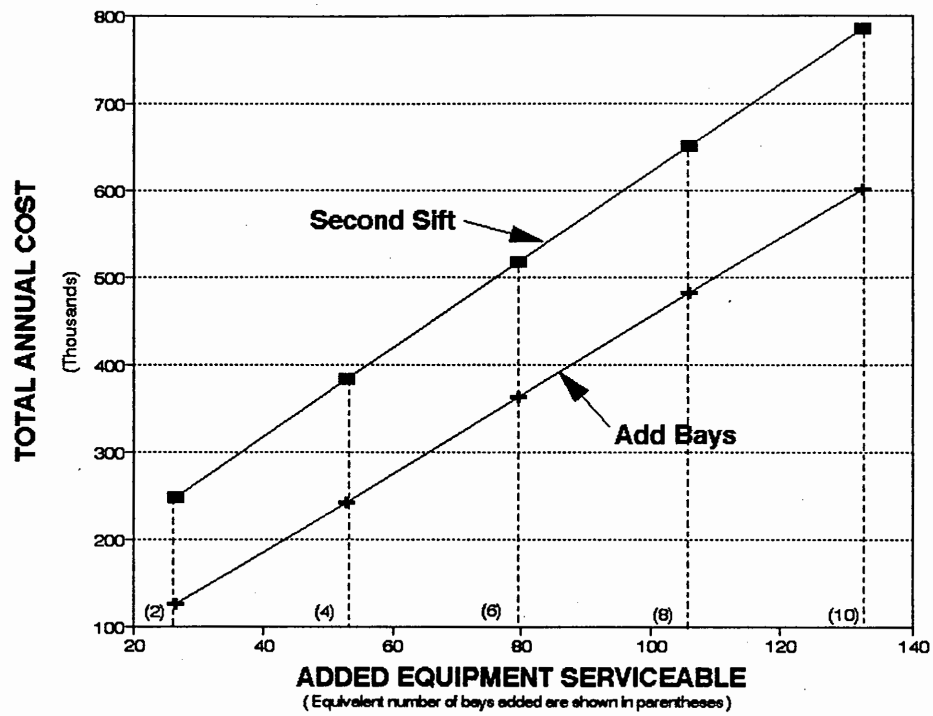


Figure 11. Comparison of adding bays versus using a second shift.

Although the second shift is not an attractive long-term option, it might be considered in conjunction with the recommended ten facility option as a possible interim measure to enable facilities to be closed earlier. To implement the recommended ten facility option, new construction is required to add bays at Wethersfield and Waterbury. This construction will have a significant lead time, which will delay the recommended closings and associated cost savings. However, it is conceivable that second shifts could be used at Waterbury and Wethersfield until the new bays are completed, at which point the sites would switch to expanded first shift operations. Of course, this would have a severe impact on the mechanics transferred from the closed facilities, since they would be required to change their work place (permanently) <u>and</u> their work hours (temporarily). To keep the disruptions associated with work force changes at a more manageable level, we do not recommend using a second shift as a temporary measure at Waterbury and Wethersfield if the ten facility option is adopted. In our opinion, a better alternative would be to take all possible steps to accelerate the construction of new bays so that the savings of that option could be realized quickly.

As mentioned earlier, the eleven facility option involves no new construction, so its savings can be achieved immediately. Therefore, if that option is adopted there would be no need to consider the use of second shift operations as an interim measure.

Future Research

At the beginning of this report in the "Scope and Objectives" section, a number of underlying assumptions of this study were discussed. Elimination of the more restrictive of these assumptions is an attractive way of extending the research in the future.

Two of the major assumptions are: 1) the locations where pieces of equipment are housed remain fixed; and 2) the level of roadway maintenance provided by the State remains unchanged. These two assumptions enabled the used of a single-level facility location model, which focuses strictly on the equipment repair facilities. Eliminating these assumptions would result in a more complex model, but optimization methods could still be used to analyze the system. There are obvious interdependencies between the level of roadway maintenance, the locations of roadway maintenance garages, and the locations of equipment repair facilities. An optimization model that reflects these interdependencies would be a very useful tool for investigating the cost implications of alternative strategies for meeting the State's roadway maintenance requirements.

Besides building a more sophisticated optimization model, other areas of future research could also yield benefits. Two possibilities for study that became apparent over the course of the current research are: 1) development of scheduling procedures for the equipment repair facilities; and 2) refinement of methods for managing inventories at the repair facilities. Although these topics are not likely to result in recommendations that offer the same magnitude of savings as a more sophisticated optimization model, research in these other areas is likely to result in improvements that would easily justify the cost of the studies.

The costs to the State of the research studies being recommended should not be underestimated. The current study, for example, required many hours of work by several people within ConnDOT. Although the salaries of these employees were fixed, the time they spent on this research has had costs in terms of time taken away from other important concerns. Given the investment that the State has already made in the optimization model used for this study, ConnDOT would be well-advised to make further use of it in the future. At the very least, the existing model should be used to investigate cost implications of any changes to equipment repair facilities being considered.

Our strongest recommendation for future research is to build upon the current model to include variable locations of roadway maintenance garages and variable levels of State-provided roadway maintenance. Extensions along these lines are likely to provide substantial additional savings for the State.

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APPENDIX A. OVERHEAD COSTS OF FACILITIES AND EXPANSIONS

This appendix discusses the derivation of the K_f, M and N parameters present in the objective function of the optimization model shown in Section III. K_f represents the cost of keeping facility f open, and M and N reflect costs of expanding facilities by adding workbays. The phrase "overhead costs" is somewhat misleading, because the values derived for these parameters reflect considerations that go beyond the typical definition of overhead. For example, revenue from the sale of property is included where appropriate in the K_f values, and construction costs are reflected in the M and N parameters. Development of each of these parameters is discussed individually below.

One of the major components of the K_f parameters for a number of facilities is the revenue that would be generated if the facilities were to be sold. For this study, we have assumed that the repair facility site is sellable if there are no other major operations at the same site. Nine of the thirteen sites support maintenance garages in addition to repair facilities, and since considering the relocation of these maintenance garages is beyond the scope of this study, we have assumed that these sites cannot be sold if the repair facilities are closed.

The four sites without maintenance garages are: Lisbon, Higganum, Brookfield and East Haven. The Lisbon site houses a test lab, and a storage area for core samples is located at Higganum. However, both of these areas are relatively small, so we assume they can be relocated if the repair facilities are closed and the properties sold. This is discussed further in Section V, particularly with regard to the core sample storage area at Higganum.

For the four potentially sellable sites, property value estimates were obtained from the ConnDOT Rights of Way division. These estimates were adjusted downward to reflect current market conditions and estimated time on the market. The estimate for Higganum was further reduced by $ 10,000 to reflect a one-time cost of moving test boring samples located on the site. The resulting estimated revenues from the sale of these properties is shown below in Table A.1.

Table A.1 Estimated revenues from sale of properties.

Lisbon	Higganum	Brookfield	East Haven
$ 572,000	$ 480,000	$ 1,226,000	$ 1,062,000

Another source of one-time savings associated with closing a facility is a reduction in inventory levels in the store area. Through consultations with Mr. George Purdell and Mr. Edward Saller from ConnDOT Purchasing and Stores, the estimates shown in Table A.2 were developed. These estimates are based on historical data regarding inventory levels, and an assumption that 2/3 of a store's inventory would be eliminated if the facility were closed. The other 1/3 of the inventory would presumably be redistributed to other facilities to help support their increased demands.

Table A.2 One-time savings from reduction in inventory levels.

Lisbon	$ 107,000	East Granby	$ 66,000
Higganum	42,000	Waterbury	107,000
Milford	95,000	Winchester	95,000
Brookfield	67,000	Darien	68,000
Putnam	67,000	Old Saybrook	52,000
Wethersfield	166,000	West Willington	81,000
East Haven	59,000		

The other source of one-time savings that we consider is the elimination of needed improvements at a facility being closed. Working with people from the Division of Property Control, estimates were obtained for repairs needed at two of the thirteen facilities. These estimates are shown in Table A.3.

Table A.3 One-time savings from elimination of needed building repairs.

site:	Higganum	Milford
repairs:	roof, boiler, interior renovations, exhaust system.	interior renovations.
est. cost:	$ 161,000	$ 50,000

Table A.4 shows the total one-time savings for each facility, which was obtained by adding together the values in Tables A.1, A.2 and A.3. Also shown in Table A.4 is an "equivalent annual savings," which was obtained by dividing the one-time savings by a factor of 10.49. This factor is used throughout this study to put one-time payments on the same basis as annual payments. This factor reflects the present value of a 20-year stream of annual payments when the prevailing interest rate is 7.125 %. In other words, we assume an equivalence between a one-time payment of $ 10.49 and a 20-year stream of annual payments in the amount of $ 1.00. This is a standard type of assumption to make in studies involving financial data that have both annual and lump-sum components. The 7.125 % interest rate is the average rate recommended for our use by Mr. Benson R. Cohn, Assistant Treasurer in the Office of the State Treasurer.

Table A.4 Total one-time savings associated with closing facilities, and the equivalent annual savings (based on 20-year horizon and 7.125% interest rate).

	Total one-time savings	Equivalent annual savings
Lisbon	$ 679,000	$ 64,700
Higganum	683,000	65,100
Milford	145,000	13,800
Brookfield	1,293,000	123,300
Putnam	67,000	6,400
Wethersfield	166,000	15,800
East Haven	1,121,000	106,900
East Granby	66,000	6,300
Waterbury	107,000	10,200
Winchester	95,000	9,100
Darien	68,000	6,500
Old Saybrook	52,000	5,000
West Willington	81,000	7,700

Besides the annual values derived from the one-time savings shown in Table A.4, there are other sources of annual savings associated with closing a facility. Table A.5 summarizes these other annual savings, and then adds them together with the values from Table A.4 to arrive at the total annual savings shown in the last column. These totals are used as the values of the K_f parameters in the optimization model. The GAMS model shown in Appendix D establishes the K_f parameters using these values, as seen on page D.7.

Table A.5 Annual savings components and total annual savings associated with closing facilities (all values are in thousands of dollars).

	Building Expenses	Stores Personnel	Repair Personnel	Equivalent Annual savings from Table A.4	Total annual savings
Lisbon	77.9	45.1	81.1	64.7	268.8
Higganum	41.6	40.8	81.1	65.1	228.6
Milford	68.8	45.1	81.1	13.8	208.8
Brookfield	36.2	40.8	81.1	123.3	281.4
Putnam	55.9	40.8	81.1	6.4	184.2
Wethersfield	78.5	45.1	81.1	15.8	220.5
East Haven	56.7	40.8	81.1	106.9	285.5
East Granby	57.0	40.8	113.1	6.3	217.2
Waterbury	66.2	45.1	81.1	10.2	202.6
Winchester	60.6	40.8	81.1	9.1	191.6
Darien	71.8	45.1	113.1	6.5	236.5
Old Saybrook	71.8	40.8	81.1	5.0	198.7
West Willington	48.8	40.8	81.1	7.7	178.4

The annual savings components shown in Table A.5 will now be explained. Building expenses represent overhead costs for such things as heat, electricity and supplies. They also include labor charges for building upkeep. The figures shown in Table A.5 were developed with the help of Mr. George Conkling, Jr., Director of Property Control. These figures represent averages of the actual expenses incurred in fiscal 89/90 and 90/91. The values for the new facilities (i.e. Darien, Old Saybrook and West Willington) were estimated based on their square footage and the average expense per square foot at the other ten facilities. Building expenses represent a major component of the total annual savings achievable if a repair facility is closed. For buildings that house other functions besides equipment repair, the values shown in Table A.5 have been prorated to reflect savings from the repair side only.

The next two columns in Table A.5 indicate savings from elimination of positions. For the stores area, we assume that the site's supervisor position is eliminated, so the values in that column represent the store supervisor's annual salary multiplied by a factor of 1.4556 to reflect burden and fringe. Although all facilities have more than one person working in their store, we include only the supervisor's salary as savings to allow for the possibility that some stores workers will be transferred to help with increased demands at other sites.

Under the repair personnel column, the figures reflect savings from the salaries of supervisors, secretaries and janitors -- no savings from mechanics' or crew leaders' salaries are included. All facilities have one supervisor and one secretary, and the East Granby and Darien (Norwalk) sites each have one employee who performs janitorial-type of services. Again, the 1.4556 burden and fringe factor has been included in these annual salary savings.

Regarding mechanics and crew leaders, no savings from them are included because it is assumed that they would be reassigned to other facilities if their facility is closed. As far as crew leaders go, Wethersfield is the only facility that currently has more than one crew leader. Because of this precedent, we have adopted a conservative stance relative to the crew leaders by assuming that those positions would be reassigned instead of eliminated. A similar stance is adopted regarding the mechanics. The analysis presented in Appendix F is intended to assist with mechanic reassignment decisions related to the consolidation of the repair facilities.

Having presented the components of the K_f parameters, we should also mention what is <u>not</u> included in these parameters. For the repair facilities that share sites with maintenance garages, we have not included any value associated with the vacant space that would remain if the repair portion were closed. If using the space for some other purpose would benefit the State, then the K_f values for those facilities would be higher.

Also not included in the K_f figures are any salvage values associated with equipment that could be removed from the facilities. It was the opinion of people in the Division of Property Control that relocating equipment such as truck lifts and overhead cranes would not provide benefits significant enough to warrant inclusion in the model.

Another consideration which has not been included in the K_f parameters is any savings that might occur if construction were discontinued at the new facilities currently being built. We have assumed that the costs of constructing the new facilities at West Willington and Darien are sunk costs. However, if it were possible to recoup significant portions of these costs by halting repair facility construction (or by scaling back the size of the Darien facility), then the K_f value of each of these facilities would change.

This appendix will now turn to the derivation of the M and N parameters, which represent costs associated with expanding existing facilities. For this study, expansion costs are assumed to be the same at each site. Estimates for constructing additional bays were obtained from ConnDOT Rights of Way. They provided estimates for additions of 2 bays, 4 bays, and 6 bays, based on construction costs for a stand-alone building similar to building number 81-170 at the Lisbon site. Construction costs estimates provided by Rights of Way were adjusted upward to reflect engineering and site preparation costs, and also costs of including one $ 30,000 truck lift with any expansion. The adjusted values for the new construction are shown in Table A.6.

Table A.6 Costs of expanding repair facilities.

Expansion option: (square footage):	2 bays (1800 sq.ft.)	4 bays (3600 sq.ft.)	6 bays (5400 sq.ft.)
One-time costs:	$ 157,050	251,100	345,150
Equivalent Annual Costs:	14,970	23,940	32,900
Annual building expenses:	7,180	14,360	21,550
Total annual costs: ($ / year)	22,150	38,300	54,450

To put the one-time construction costs on an annual basis, we divide the one-time costs by the factor 10.49, which reflects an interest rate of 7.125 % and a 20-year time horizon, as discussed earlier.

Besides construction costs, we also consider that building expenses will increase if a facility is expanded. Estimates of additional building expenses are based on $ 3.99 / sq.ft. / year, which was derived by taking the building expense values in Table A.5 and dividing them by the square footage of the repair facilities. Using this $ 3.99 figure, we obtained the estimated annual building expenses shown in Table A.6. Adding these to the annualized construction costs results in the total annual cost figures shown in the table.

Rather than considering only the three discrete expansion options shown in Table A.6, we used the total costs from these to establish the following function:

$$\text{Annual expansion costs at facility } f = 22{,}150\ A_f + 8{,}075\ B_f$$

Where: A_f = 1 if at least 2 bays are added at facility f, 0 otherwise;

and B_f = the number of bays added above two at facility f.

$ 22,150 and $ 8,075 are the values of the parameters M and N, respectively, in the optimization model. In the GAMS model shown in Appendix D, these parameters are labelled ACOST and BCOST, and are defined as scalars on page D.7.

In using the cost function shown above, a number of assumptions are implied. First, it assumes that the minimum expansion possible is 2 work bays. Second, it assumes that one truck lift will be included with any expansion, regardless of its size. Third, fractional values of work bays can result in a solution, since the B_f variables are not restricted to be integer. Fractional B_f values were allowed due to computational considerations. Adding new sets of integer variables to the model would greatly increase computation times. Errors introduced because of fractional B_f values are minor because the N parameter, with a value of $ 8075, is relatively small.

This completes discussion of the derivation of overhead cost parameters for the optimization model. As indicated earlier, the term "overhead" is somewhat misleading because the K_f, M and N parameters include more than the typical overhead expenses. The values of these parameters have been developed to provide a fair indication of the costs associated with keeping a facility open or adding capacity to a facility.

APPENDIX B. DEMAND AND CAPACITY ANALYSIS

This appendix details how the D_i, P_f, R and S parameters present in constraint set (7) of the MIP formulation were developed. The methodology and underlying assumptions are discussed, and specific values for all parameters are tabulated.

As discussed in Section II, a single commodity formulation can be used to represent the ConnDOT repair system because all repair facilities provide service for practically all types of equipment. However, when discussing the capacity of a repair facility, i.e. how much equipment it can service, the fact that there are different types of equipment must somehow be reflected. The approach used here is to categorize equipment based on similarities of maintenance requirements. A weight is established for each category to represent the magnitude of repair requirements for equipment in that category.

The categories shown in Table B.1 were established through consultations with Mr. James E. Lewis, Jr., Equipment Repair Supervisor for ConnDOT. The appropriate categories for more than 400 subclasses of equipment were identified by Mr. Lewis for this study.

Table B.1. Equipment categories, repair hours and visit frequencies. (Standard errors of the estimates are shown in parentheses.)

Category	Description	Avg. Annual Repair Hours	Avg. Annual Visit Frequency
1-A	Heavy Truck, Dual Dump	114.0 (8.9)	9.4 (.57)
1-B	Heavy Truck, Conv. Dump	67.3 (11.4)	9.4 (3.6)
2	Light Truck	37.7 (5.7)	5.2 (.51)
3	Heavy Motorized	42.9 (10.1)	3.4 (.53)
4	Small Motorized	4.1 (1.4)	1.4 (.48)
5	Others needing maint.	10.7 (5.0)	0.7 (.26)

Once equipment was categorized, the next major task was to find the numbers of each type of equipment at each garage. For this, the "PM PLANNER" software developed by the Office of Maintenance proved to be extremely useful. PM

PLANNER is a personal computer-based program which contains records for all equipment in the repair system. We printed out lists of equipment, by maintenance garage, and then counted the number of pieces in each category at each garage.

Define G_{ei} as the quantity of equipment in category e housed at garage i. The total load offered by garage i, in terms of repair requirements, is calculated as follows:

$$D_i = \sum_{e=1A}^{5} W_e G_{ei}$$

Where: W_e is the weight given to equipment in category e.

For the capacity constraint set (7) in the MIP formulation, the relevant limited resource is the number of work bays at the repair facility. Therefore, W_e values are designed to reflect usage of work bays. According to Mr. Lewis, equipment in categories 1A though 3 all use a full bay for repair, whereas the vast majority of equipment in categories 4 and 5 can be repaired on work benches or in other space which does not tie up an entire bay. Based on this, the following weights were used for establishing D_i values:

$W_{1A} = 1$, $W_{1B} = 0.59$, $W_2 = 0.33$, $W_3 = 0.38$, $W_4 = 0$, and $W_5 = 0$.

The weight for each of categories 1A through 3 is equal to the average annual repair hours for equipment in that category divided by the annual repair hours for equipment in category 1A. Average annual repair hours and average annual visit frequencies were established by taking a random sample of 100 pieces of equipment in each category, and then looking in detail at their repair histories using the Equipment Analyzer feature of the PM PLANNER software. These averages and associated standard errors of the estimates are shown in Table B.1.

In Appendix D, the table labelled G(I,E), which starts on page D.7, shows the counts of equipment located at each of the 76 sources of repair requirements. Also in the GAMS model, on page D.14, the W_e parameters are specified for the model, and then D_i values (called DEM(I) in the GAMS model) are calculated as specified above. Table B.2 below lists the 55 garages and 21 other sources of equipment. It also displays D_i values and other information about them.

Table B.2 Major sources of repair requirements.

GAMS Label	Building #	Town	Function	D_i	Current Repair Facility
GAR1	81-602	North Canaan	Maintenance Garage	7.20	Winchester
GAR2	81-803	Norfolk	Maintenance Garage	6.44	"
GAR3	81-060	Torrington	Maintenance Garage	21.24	"
GAR4	81-613	Winchester	Maintenance Garage	27.40	"
GAR5	81-574	Cornwall	Maintenance Garage	10.85	"
GAR6	81-209	Sharon	Maintenance Garage	3.89	"
GAR7	81-149	Litchfield	Maintenance Garage	13.05	"
GAR8	81-425	New Milford	Maintenance Garage	14.67	Brookfield
GAR9	81-167	Southbury	Maintenance Garage	14.86	"
GAR10	81-143	Danbury	Maintenance Garage	16.16	"
GAR11	81-113	New Canaan	Maintenance Garage	12.73	Darien
GAR12	81-129	Darien	Maintenance Garage	20.27	"
GAR13	81-132	Westport	Maintenance Garage	22.45	"
GAR14	81-130	Fairfield	Maintenance Garage	11.99	"
GAR15	81-600	Waterbury	Maintenance Garage	23.87	Waterbury
GAR16	81-607	Thomaston	Maintenance Garage	18.10	"
GAR17	81-369	Southington	Maintenance Garage	13.15	"
GAR18	81-678	Beacon Falls	Maintenance Garage	16.45	"
GAR19	81-009	Orange	Maintenance Garage	18.35	Milford
GAR20	81-144	Milford	Maintenance Garage	45.00	"
GAR21	81-134	Stratford	Maintenance Garage	19.36	"
GAR22	81-157	Branford	Maintenance Garage	13.04	East Haven
GAR23	81-147	New Haven	Maintenance Garage	14.19	"
GAR24	81-136	North Haven	Maintenance Garage	13.47	"
GAR25	81-251	Wallingford	Maintenance Garage	32.90	"
GAR26	81-261	Farmington	Maintenance Garage	16.65	Wethersfield
GAR27	81-236	East Hartford	Maintenance Garage	18.61	"
GAR28	81-008	Glastonbury	Maintenance Garage	15.35	"
GAR29	81-131	Meriden	Maintenance Garage	15.11	"
GAR30	81-126	Meriden	Maintenance Garage	14.84	"
GAR31	81-171	Avon	Maintenance Garage	11.33	East Granby
GAR32	81-003	Simsbury	Maintenance Garage	5.08	"
GAR33	81-011	East Granby	Maintenance Garage	8.73	"
GAR34	81-010	East Windsor	Maintenance Garage	20.13	"
GAR35	81-169	Windsor	Maintenance Garage	13.53	"
GAR36	81-633	Vernon	Maintenance Garage	18.83	West Willington
GAR37	81-004	Union	Maintenance Garage	6.73	"
GAR38	81-212	West Willington	Maintenance Garage	18.49	"
GAR39	81-643	Mansfield	Maintenance Garage	5.23	"
GAR40	81-125	Bolton	Maintenance Garage	14.52	"
GAR41	81-007	Middletown	Maintenance Garage	14.34	Higganum
GAR42	81-606	Marlborough	Maintenance Garage	13.14	"
GAR43	81-601	Colchester	Maintenance Garage	22.31	"
GAR44	81-220	Tylerville	Maintenance Garage	19.14	"
GAR45	81-161	Guilford	Maintenance Garage	11.97	Old Saybrook
GAR46	81-610	Waterford	Maintenance Garage	13.18	"
GAR47	81-671	Old Saybrook	Maintenance Garage	26.82	"
GAR48	81-165	Franklin	Maintenance Garage	13.32	Lisbon
GAR49	81-175	Occum	Maintenance Garage	16.99	"
GAR50	81-155	Groton	Maintenance Garage	15.44	"
GAR51	81-173	Norwich	Maintenance Garage	13.72	"
GAR52	81-630	Canterbury	Maintenance Garage	11.14	Putnam
GAR53	81-023	Pomfret	Maintenance Garage	12.77	"
GAR54	81-174	Putnam	Maintenance Garage	19.86	"
GAR55	81-235	Wethersfield	Maintenance Garage	38.55	Wethersfield
OTH1	85-043	Oxford	Airport	5.47	Brookfield
OTH2	81-013	Wolcott	Sand & Salt	7.15	Waterbury
OTH3	81-146	Hamden	Signs & Marking	2.95	Milford
OTH4	81-146	Hamden	Signs & Marking	9.93	East Haven
OTH5	81-128	Wethersfield	Administrative Bld.	6.83	Wethersfield

OTH6	81-016	Hartford	Bridge Repair Bld.	3.96	Wethersfield
OTH7	81-145	East Hartford	Signs & Marking	6.84	"
OTH8	85-003	Hartford	Airport	6.54	"
OTH9	81-016	Hartford	Elec. Repair Bld.	25.39	East Granby
OTH10	85-335,-014,-038	Groton	Airport	4.91	Old Saybrook
OTH11	81-127	Old Saybrook	Bridge Repair Bld.	9.78	Old Saybrook
OTH12	81-247	Montville	Elec. Repair Bld.	5.31	Lisbon
OTH13	81-176	Plainfield	Signs & Marking	10.11	Putnam
OTH14	81-315	Newington	PC Gar. Off.	8.96	Wethersfield
OTH15	81-096	Rocky Hill	Res. Lab	13.13	"
OTH16	81-092	Wethersfield	Annex	2.36	"
OTH17	81-609	Rocky Hill	District I Hqtrs.	4.95	"
OTH18	81-322	North Windham	Maintenance Garage	13.34	West Willington
OTH19	81-100	Portland	Gar. & Off.	8.86	Higganum
OTH20	81-172	East Lyme	Maintenance Garage	7.54	Old Saybrook
OTH21	81-104	Norwich	District II Hqtrs.	5.61	Lisbon

Besides the major sources of requirements included in Table B.2, small amounts of equipment come to repair facilities from other sources as well. Because there are many minor sources and their requirements are relatively small, they are not considered in the model. Also excluded from the analysis is equipment assigned to and located at the repair facilities themselves. This equipment is excluded because we do not know what would happen to a facility's equipment if the facility were closed. Overall, the equipment located at repair facilities plus equipment from other minor sources accounts for less than 10 % of system-wide repair requirements. Note that this equipment is excluded from both the demand <u>and</u> capacity parameters -- i.e. the Q_f values shown later on do not consider the excluded equipment currently served by the facilities. Excluding this equipment when developing the capacity parameters helps to offset the fact that it is not included in the model's system-wide demand.

With the D_i values of all major sources known, the total load currently being served by each repair facility can be calculated by summing up the D_i values of all locations served by the facility. As an example of this consider Brookfield, which currently serves garages located at New Milford, Southbury and Danbury, and a small airport in Oxford. Summing up the D_i values for these sources, we obtain the following:

$$Q_{Brookfield} = D_{GAR8} + D_{GAR9} + D_{GAR10} + D_{OTH1}$$

$$Q_{Brookfield} = 14.67 + 14.86 + 16.16 + 5.47 = 51.16$$

Where $Q_{Brookfield}$ = the weighted average quantity of equipment served by Brookfield.

Figure B.1 shows Q_f values as a function of the number of work bays at each facility. The numbers of work bays shown in this figure reflect the total numbers of bays, including specialty bays such as those used for welding and painting. The data for the numbers of bays shown in Figure B.1 was obtained through visits to all 13 active equipment repair facilities.

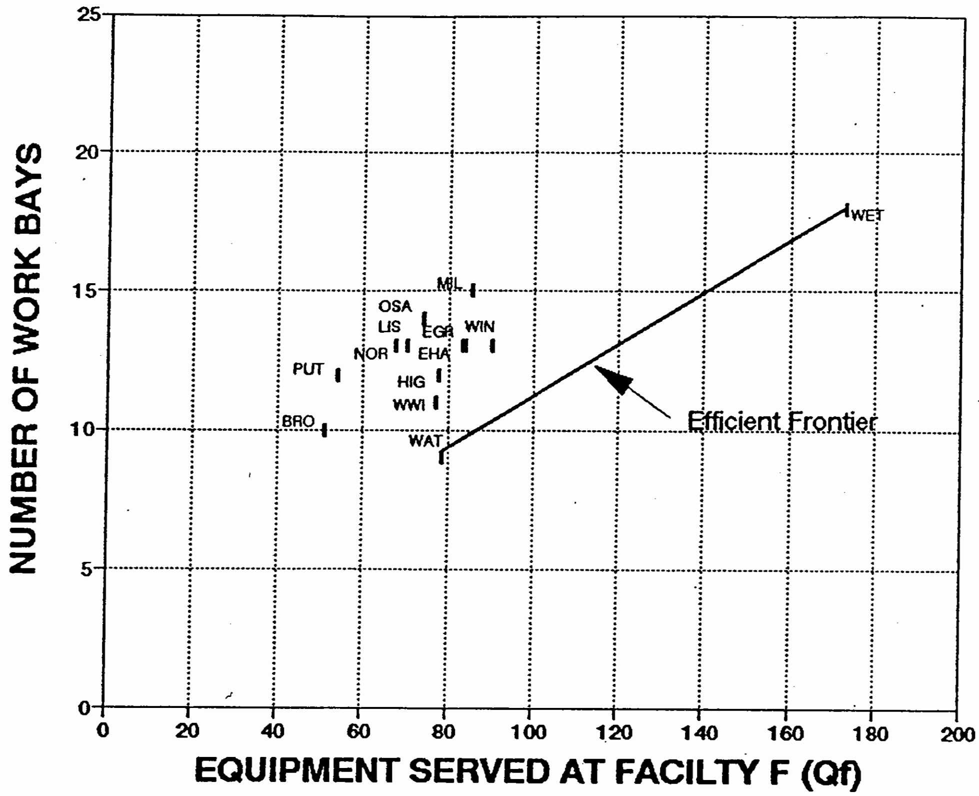


Figure B.1 Number of work bays versus quantity of equipment served at each facility.

From Figure B.1, it is apparent that some facilities have a higher utilization of work bays than others. Without looking at absolute utilization levels, it can be seen from Figure B.1 that excess capacity exists at some of the facilities because other facilities serve the same amount of equipment with fewer work bays. By choosing as benchmarks the facilities that serve large amounts of equipment for their numbers of bays, an "efficient frontier" is established, as shown in Figure B.1. The label "efficient frontier" is somewhat misleading because the facilities that fall on it are not necessarily the most efficient in all respects, nor are facilities that are not on the frontier necessarily deficient in any sense. With 13 facilities in the system, it is not surprising to find differences in the utilization of work bays across facilities. The reason for establishing the "efficient frontier" is to indicate the load that can be served by a given number of bays, based on the loads being handled by the more highly utilized facilities within the system.

There can be a difference between the quantity of equipment <u>served</u> by a facility (Q_f) and the quantity of equipment <u>serviceable</u> at that facility, which we label P_f. More specifically, the following relationship applies:

$$P_f \geq Q_f$$

For the two benchmark facilities (Waterbury and Wethersfield), $P_f = Q_f$. For those not on the efficient frontier, the frontier is used to find the value of equipment serviceable associated with the number of work bays at the facility, as illustrated in Figure B.2. In Figure B.2, Darien is shown instead of Norwalk, because Norwalk is being replaced by Darien in the near future. Figure B.2 also reflects information for the new facility at West Willington, which happens to have the same number of bays as the existing facility there. Table B.3 summarizes the numbers of work bays, Q_f and P_f values for all facilities.

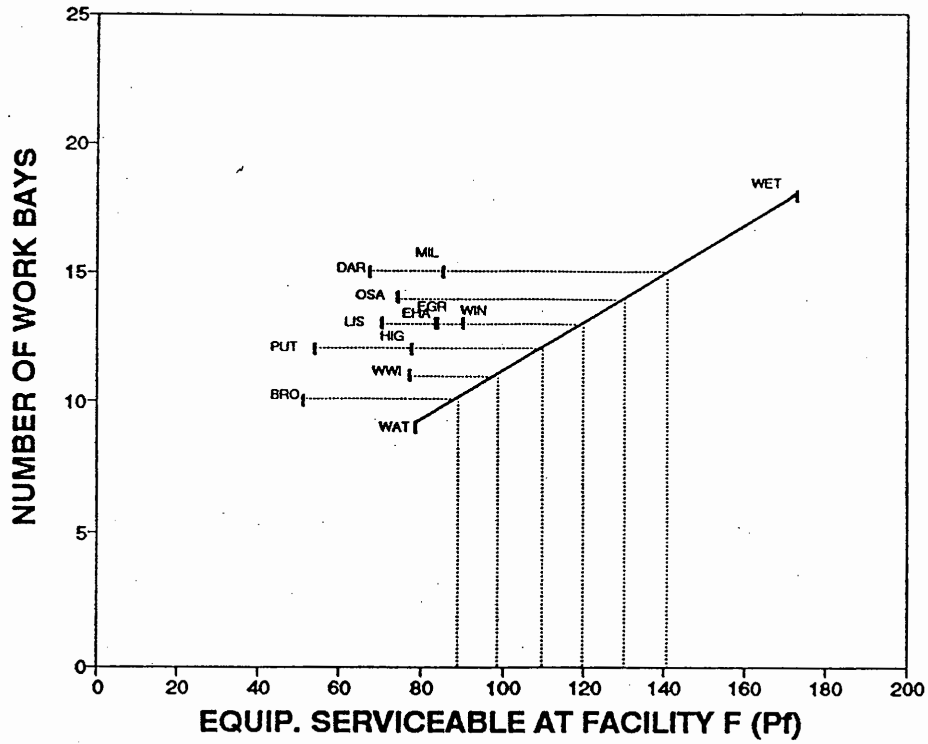


Figure B.2. Number of work bays versus quantity of equipment serviceable at each facility.

Table B.3. Number of work bays, Q_f and P_f for each facility.

Facility	Number of Bays	Q_f	P_f
Winchester	13	90.07	120.48
Brookfield	10	51.16	89.16
Darien (Norwalk)	15	67.44	141.36
Waterbury	9	78.72	78.72
Milford	15	85.66	141.36
East Granby	13	84.19	120.48
Wethersfield	18*	172.68	172.68
East Haven	13	83.53	120.48
West Willington	11	77.14	99.60
Higganum	12	77.79	110.04
Old Saybrook	14	74.20	130.92
Putnam	12	53.88	110.04
Lisbon	13	70.39	120.48

	168		

(* The number of bays for Wethersfield has been adjusted upward by one to reflect that site's current practice of off-loading some work to Putnam.)

The efficient frontier shown in Figure B.1 is also used to establish the additional capacity added by building extra bays. Since the efficient frontier is a straight line, a fixed amount of capacity is added as each new bay is added. The line is defined by the values of Waterbury and Wethersfield, which are: (bays=9, Q_f=78.72) for Waterbury, and (bays=18, Q_f=172.68) for Wethersfield. The capacity added per bay, therefore, is calculated as follows:

change in Q_f / change in bays = 93.96 / 9 = 10.44.

This value represents the parameter S, which is the marginal capacity added when a bay is added. The parameter R, which is the capacity added when the first two bays of an expansion are added, is simply twice this amount, or 20.88. In the GAMS model shown in Appendix D, the R and S parameters are called ACAP and BCAP, respectively, because they go along with the A and B decision variables. These parameters are defined as scalars in the GAMS model on page D.7.

In concluding this appendix, it should be mentioned that the efficient frontier shown in Figure B.1 may not represent the true limit of equipment serviceable by facilities -- it only reflects a level of performance that has already been achieved. Although it is conservative to base the analysis on established operating levels, it is also desirable to investigate the implications of operating at a higher level. The results presented in Section IV include scenarios where demand levels are reduced by 10 and 20 %. The reduction of demand levels has a similar effect to increasing P_f values. Therefore, the demand sensitivity analysis provides an indication of how solutions would change if the efficient frontier shown in Figure B.1 were shifted by various degrees.

APPENDIX C. TRANSPORTATION COSTS

The C_{fi} parameters in the optimization model represent the annual costs incurred if all equipment from garage i is sent to facility f for repair. This appendix describes how the C_{fi} parameters were estimated for this study.

As discussed in Appendix B, equipment requiring maintenance is divided into the six categories shown in Table B.1. These same categories are used in estimating transportation costs. A separate partial cost function is developed for each equipment category. These partial costs are then summed together, and another partial cost associated with separate trips from garages to stores is also added in. Thus, seven partial costs combine to make up each C_{fi} value. The seven transportation cost components are discussed individually below.

<u>Category 1A -- Heavy truck, dual dump</u>

The transportation costs for category 1A equipment are based on the following scenario:

a) The equipment is driven from the maintenance garage to the repair facility by a driver.

b) The driver is followed to the repair facility by a second driver in a separate vehicle.

c) After the equipment has been left for repair, the second driver picks up the first driver from the repair garage and brings him back to the maintenance garage.

d) When the equipment is ready to be picked up, the second driver brings the first driver back to the repair garage and drops him off.

e) The first and second drivers return to the maintenance garage in separate vehicles.

The following costs are incurred in this scenario:

1) Equipment costs for:
   i) one round-trip by the equipment being repaired; and
   ii) two round-trips by the vehicle used by the second driver.

2) Labor costs for two round trips by each of the two drivers.

Equipment costs are assumed to be proportional to distance travelled. These costs, on a per mile basis, are shown in Table C.1. Assuming the vehicle used by the second driver is a class 1A vehicle (which is typical), then the equipment costs for a single visit for repair by a 1A vehicle are as follows:

$$\text{Cat. 1A equipment costs per trip} = (\text{DIST}(I,F)*2) * (.78 + .78*2)$$

$$= \text{DIST}(I,F) * 4.68$$

Where DIST(I,F) is the one-way travel distance between garage i and facility f, in miles.

Table C.1. Equipment transportation costs.

Equipment Category	Operating Cost[1] per mile	Capital Cost[2] per mile	Total Cost per mile
1A	.49	.29	$ .78
1B	1.17	.27	1.44
2	.13	.09	.22
3	.90	.32	1.22
low-bed trailer	1.87	.69	2.56

[1] Estimated by taking total annual operating costs, which include fuel and maintenance expenses, and dividing by total annual miles.

[2] Estimated by taking total equipment cost, less salvage value, and dividing by the number of miles in useful life.

Table C.2. Labor costs for transportation.

Equipment Category	Hourly rate of operator	Hourly Overtime rate	Hourly rate including fringe and burden[1]
1A	14.35	21.53	31.34
1B	14.35	21.53	31.34
2	15.78	23.67	34.45
3	15.62	23.43	34.10
low-bed trailer	15.62	23.43	34.10

[1] Reflects multiplicative fringe and burden factor of 1.4556.

For the labor component, Table C.2 shows the hourly wage rate (including fringe and burden) for the drivers associated with equipment types 1A through 3. These values are based on an assumption that all equipment transportation will be done on an overtime basis (time-and-one-half pay). This assumption is conservative because many trips can actually be done during regular hours at the normal pay rate. Using the value from Table C.2 for category 1A labor, we obtain the following:

Cat. 1A labor cost per trip = (TIME(I,F)*2) * (31.34*2 + 31.34*2)

= TIME(I,F) * 250.72

Where TIME(I,F) is the one-way travel time between garage i and facility f, in hours.

To obtain an annual cost estimate associated with category 1A equipment, we also need to consider the quantity of that type of equipment at garage i and the average number of times per year that the equipment visits a repair facility. The average number of visits per year, which was estimated using the historical records contained in the PM PLANNER software database, was shown previously in Table B.1. Using the estimate from that table, the complete partial transportation cost function for category 1A is as follows:

Annual transportation costs for Cat. 1A =

$$(DIST(I,F)*4.68+TIME(I,F)*250.72)*9.4*G_{1A,i}$$

Where $G_{1A,i}$ is the quantity of type 1A equipment at garage i, as discussed in Appendix B.

Looking at page D.15 of the GAMS model shown in Appendix D, the partial transportation cost functions can be seen in the format understood by the GAMS software. Two other components of the partial transportation functions in the GAMS model are: 1) the constant 1.09; and 2) the constant 1000. The 1.09 represents an circuity factor included to transform the distances and times tabulated in the GAMS model into more accurate estimates. The constant 1000 converts the cost figures into thousands of dollars. With these two additions, the partial cost function shown in the GAMS model for category 1A equipment corresponds directly to that presented above. The same is true for the cost function of each of the other equipment categories.

Category 1B -- Heavy truck, conventional dump

The assumptions underlying the transportation cost function for category 1B equipment are the same as those for category 1A. Using data from Tables C.1, C.2 and B.1, the partial cost function is developed as follows:

Category 1B equipment costs per trip = (DIST(I,F)*2) * (1.44 + .78*2)

= DIST(I,F) * 6.00

Category 1B labor costs per trip = (TIME(I,F)*2) * (31.34*2 + 31.34*2)

= TIME(I,F) * 250.72

Annual transportation costs for cat. 1B =

$$(DIST(I,F)*6.00 + TIME(I,F)*250.72)*9.4*G_{1B,i}$$

Category 2 -- Light Truck

Continuing along the same lines as the previous two categories, the transportation costs for category 2 are as follows:

Category 2 equipment costs per trip = (DIST(I,F)*2) * (.22 + .78*2)

= DIST(I,F) * 3.56

Category 2 labor costs per trip = (TIME(I,F)*2) * (34.45*2 + 31.34*2)

= TIME(I,F) * 263.16

Annual transportation costs for cat. 2 =

$$(DIST(I,F)*3.56 + TIME(I,F)*263.16)*5.2*G_{2,i}$$

Category 3 -- Heavy Motorized

Pieces of category 3 equipment require special treatment because the assumptions underlying their transportation are distant-dependent. We assume that a piece of category 3 equipment can be driven to a repair facility if that facility is within ten miles of the maintenance garage where the equipment is housed. Otherwise, we assume that a low-bed trailer is required to transport the equipment. The cost functions under these two scenarios are outlined individually below.

Scenario 1 -- category 3 equipment travelling 10 miles or less

The assumptions behind transportation costs for category 3 equipment travelling 10 miles or less are the same as those outlined for equipment in category 1A. Following the format previously outlined, the cost function is developed as follows:

Category 3 equipment costs per trip (dist. $\leq$ 10 miles) = (DIST(I,F)*2) * (1.22 + .78*2)

= DIST(I,F) * 5.56

For the labor costs of category 3 equipment driven in for repair, we must consider the fact that the equipments' average speed is only about 1/3 that of a normal vehicle. Consequently, a factor of 3 is multiplied by the hourly rate of the driver for the portion of time he is driving the heavy equipment. This results in the following labor costs and total annual costs:

Category 3 labor costs per trip (dist. $\leq$ 10 miles) = (TIME(I,F)*2) * (34.10*3 + 34.10 + 31.34*2)

= TIME(I,F) * 398.16

Annual transportation costs for cat. 3 (dist. $\leq$ 10 miles) =

$$(DIST(I,F)*5.56 + TIME(I,F)*398.16)*3.4*G_{3,i}$$

In the GAMS model shown in Appendix D, the expression (G(I,E) - SUB(I,E)) is used in place of G(I,E) for the partial cost functions of equipment in categories 3 and 5. This occurs because some equipment was represented by joint categories involving categories 3 and 5. For example, for the purposes of representing repair requirements, some equipment was categorized as "1A+3." To avoid double-counting when calculating transportation costs, the second component of the compound category is dropped. The SUB(I,E) table beginning on page D.8 of Appendix D shows quantities corresponding to the second component of the compound equipment. Note that non-zero entries occur for only categories 3 and 5 in this table.

Scenario 2 -- category 3 equipment travelling more than 10 miles

When equipment in the heavy motorized category must travel more than 10 miles for repair, we assume that a low-bed trailer is required to transport the equipment. The transport is assumed to be accomplished in the following steps:

a) A low-bed trailer is sent from the repair facility to the maintenance garage.

b) The equipment requires 15 minutes to be loaded onto the low-bed trailer at the maintenance garage.

c) The equipment is transported to the repair facility.

d) The equipment requires 15 minutes to be unloaded.

e) - h) Steps similar to a) - d) are repeated to return the equipment to the maintenance garage after it has been repaired.

The equipment costs associated with this transport are due to two round-trips with the low-bed trailer. These costs are estimated as follows:

Category 3 equipment
costs per trip = (DIST(I,F)*2) * (2.56*2)
(dist. > 10 miles)
= DIST(I,F) * 10.24

The labor costs in this case have two components -- one fixed and one time-dependent. The fixed component is due to two operators' wages during the load/unload times involved in the moves, which total one hour. The time-dependent component reflects the wages of a single operator over the total transportation time. The resulting function is shown below:

Category 3 labor
costs per trip = (34.10*2) + (TIME(I,F)*2) * (34.10*2)
(dist. > 10 miles)
= 68.20 + TIME(I,F) * 136.40

Combining the equipment and labor components results in the following:

Annual transportation
costs for cat. 3 =
(dist. ≥ 10 miles)

$$(68.20+DIST(I,F)*10.24+TIME(I,F)*136.40)*3.4*G_{3,i}$$

Category 4 -- Small motorized

Small motorized equipment is assumed to be transported for repair in either a heavy truck or a light truck. Equipment costs for the transport are based on an average of the 1A and 2 equipment categories. Considering that two round trips are required for each instance of repair, we obtain the following:

Category 4 equipment costs per trip = (DIST(I,F)*2) * (.50*2)

= DIST(I,F) * 2.00

Category 4 labor costs per trip = (TIME(I,F)*2) * (32.90*2)

= TIME(I,F) * 131.60

Annual transportation costs for cat. 4 =

$$(DIST(I,F)*2.00 + TIME(I,F)*131.60)*1.4*G_{4,i}$$

Category 5 -- Others requiring some maintenance

Category 5 equipment transport is based on the same assumptions as category 4, resulting in the following:

Annual transportation costs for cat. 5 =

$$(DIST(I,F)*2.00 + TIME(I,F)*131.60)*0.7*G_{5,i}$$

Trips from garage to store

Besides sending equipment to the repair facilities, the maintenance garages also use the stores located on the repair facility site. Through consultations with stores personnel, it was estimated that an average of 26 trips per year are made by each maintenance garage solely for the purpose of visiting a store. Assuming these trips are made in either a 1A or 2 category vehicle, we obtain the following:

Equipment costs for each visit to store = (DIST(I,F)*2) * (.50)

= DIST(I,F) * 1.00

Labor costs for
each visit to store = (TIME(I,F)*2) * (32.90)

= TIME(I,F) * 65.80

Annual transportation
costs for stores visits =

(DIST(I,F)*1.00 + TIME(I,F)*65.80) * 26

This component of the transportation cost is added into the GAMS model on page D.15, where the C(F,I) value is obtained by summing up the partial costs over all equipment categories. Resulting C(F,I) values can be seen in the objective function shown in the detailed output from the GAMS model run, which begins on page D.16 of Appendix D.

Estimation of Travel Distances and Times

The DIST table in the GAMS model, which begins on page D.9 of Appendix D, contains estimates of the distances between garages and repair facilities. These estimates were obtained using a computer-based road network composed of nodes (major intersections) and links (roadways). The form of this network is such that straight-line distances are used between nodes, resulting in underestimation of actual travel distances. To correct for this, a circuity factor of 1.09 is included in the model when calculating transportation costs, as discussed previously. Multiplying the tabulated distances by this empirically-derived circuity factor provides better estimates of actual distances.

The quickest path from each garage to each repair facility was determined by considering distances and travel speeds along each of the roads in the network. The travel times shown in the GAMS model, which begin on page D.12, reflect these quickest paths, as do the distances. As with the distances, the travel times are also multiplied by the circuity factor to provide more realistic estimates.

For all values associated with distances greater than 40 miles, the value 9999 is shown in the GAMS tables for both DIST and TIME. These entries, which cut down significantly on the amount of calculations required, constrain solutions such that no equipment will travel more than 40 miles for repair. Because no equipment travels more than about 20 miles for repair in the existing system, the 40 mile limit was not considered to be a serious limitation for this application.

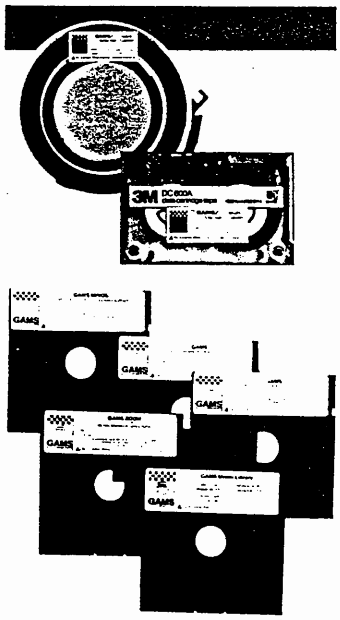
APPENDIX D. OPTIMIZATION SOFTWARE AND INPUT / OUTPUT

This appendix presents information regarding the optimization software used in this study, and it also displays samples of input and output. The software is a personal computer version of GAMS (General Algebraic Modelling System), which is distributed by The Scientific Press, South San Francisco, California. The next five pages of this appendix present material duplicated out of a catalog from The Scientific Press. After that material, selected samples of input and output from the GAMS model developed for this study are displayed.

The GAMS model corresponds closely to the mixed-integer programming model developed in Section III. Two constraints in the GAMS model, which are both show on page D.15, do not correspond directly to the model shown in Section III. One of these is the constraint labelled "TOTFAC," which is explained in Section IV. The other extra constraint set, which is labelled "TIGHTEN," was added purely for computational reasons -- these constraints do not affect resulting solutions because they are redundant to the supply constraints when Y(F) variables are integer.

To reduce length and add clarity, some of the less relevant and highly technical input and output have been excluded from this report. The material included provides a good indication of how parameters of the model are entered into GAMS, and the manner in which GAMS displays solutions after it is done solving a problem.

GAMS Software



GAMS (General Algebraic Modeling System) **developed by Alexander Meeraus and Anthony Brooke, both formerly of the World Bank, now at GAMS Development Corp.**

MINOS (Modular Incore Nonlinear Optimization System) **developed by Bruce Murtagh, University of South Wales, Michael Saunders, Stanford University**

ZOOM **developed by Roy Marsten, University of Arizona**

For price and ordering information on GAMS, please see page 35 of this catalog.

GAMS (General Algebraic Modeling System) is a general purpose optimization system, specifically designed for modeling and solving large and complex linear, nonlinear, and mixed integer programming problems. Available for the PC, 386, workstation, or mainframe, GAMS will allow you to concentrate on model building and development while it takes care of the time-consuming details of machine implementation for you. GAMS is especially useful for handling large, complex, "one of a kind" problems, which may require many revisions of the model to get the formulation right. It will enable you to model problems in a highly compact and natural way and to change your formulation quickly and easily—even convert a model from linear to nonlinear with little trouble.

GAMS is easy to learn and comes with *GAMS: A User's Guide*, a complete tutorial and reference manual (see below). A model library containing 100 machine-readable models developed in GAMS is also available to purchasers.

You can also use GAMS as a powerful teaching tool: a student version is also available (details below).

System Requirements

- PC version: DOS-compatible PCs with hard disk, 512K RAM (640 recommended), PC-DOS or MS-DOS version 2.0 or higher. Math coprocessor recommended.
- 386 and workstation version: Runs on DOS-compatible 80386 computers with 80287/80387 or Weitek math coprocessor. Also SUN 3, SUN 4, SUN SPARCstation, SUN 3861; Apollo 3000, 4000, 10000 series; DEC MicroVAX (VMS or UNIX), DEC station 3100 (UNIX), VAX station (VMS or UNIX); Hewlett-Packard HP 9000, 300 & 800 series; MIPS; and UNISYS (UNIX).
- Mainframe version: Runs on IBM (VM/CMS, MVS/TSO), DEC VAX (VMS or UNIX), CRAY (UNICOS), BURROUGHS, and ALLIANT.

System Dimensions

- Base GAMS module. Handles 32,767 rows and columns with a maximum of 32,767 elements.
- GAMS/MINOS module. Handles 32,767 rows and columns with a maximum of 2,147,483,647 nonzero elements and 32,767 nonlinear nonzeroes.
- GAMS/ZOOM-XMP module. Practical design limit is about 200 zero/one variables.
- MPSX link (mainframe only). Provides interface capability between GAMS base module and IBM's MPSX solver.

Features

- **GAMS Lets the User Concentrate on Modeling**

  Increases the time spent on conceptualizing the model, running it, and analyzing the results.

  Eliminates the need to think about purely technical, machine-specific problems such as address calculation, storage assignments, subroutine linkages and input-output and flow control.

  Encourages good modeling habits by requiring concise and exact specification of entities and relationships.

- **GAMS Is Straightforward to Learn and Use**

  The GAMS language is formally similar to FORTRAN. It will seem familiar to anyone with programming experience.

  Models are described in concise algebraic statements so models are as easy for humans as well as machines to read. (See below for an actual example.)

  Whole sets of closely related constraints are entered in one statement. GAMS automatically generates each constraint equation, based on the input of general algebraic formulas and specific data values. (Note: GAMS lets you make any exceptions you want in cases where generality is not desired.)

Data are entered only once in familiar list and table form.

Statements in models can be reused when other instances of the same or related problems arise. You can enter new data without having to change the algebra.

Errors are pinpointed quickly—where they are and of what type—before a solution has been attempted. GAMS automatically checks for errors in syntax, numerical operations (e.g., division by zero), and mathematical consistency (e.g., a model designated as linear which contains nonlinearities).

- **GAMS Is Flexible and Powerful**

GAMS handles linear, nonlinear and mixed integer optimization problems.

GAMS generates models independent of the solution algebra of specific solvers. You can formulate linear, nonlinear and integer problems following the same rules. You can use this feature to great advantage—for example, to develop and test alternate versions of a model within one document: one formulation might be linear, another nonlinear.

GAMS models are fully portable from one computer environment to another so long as it is loaded in both. A model can be developed on an IBM PC and solved later on a VAX.

GAMS facilitates sensitivity analysis. You can easily program your model to solve for different values of an element and generate an output report listing the solution characteristics for each case.

Models can be developed and documented simultaneously because GAMS allows you to include explanatory text as part of the definition of any symbol or equations. GAMS automatically incorporates your comments into the output report.

GAMS handles dynamic models involving time sequences, lags, leads, and the treatment of temporal endpoints.

A Model Library of 100 Machine-readable Models Is Available to Users Free

(The number of models in each field is given in parentheses.)

Agricultural Economics (12)
Forestry (2)
Applied General Equilibrium (3)
International Trade (2)
Chemistry and Chemical Engineering (3)
Macroeconomics (4)
Econometrics (3)
Engineering (2)
Management/Operations Research (22)
Mathematics (11)
Economic Development (5)
Microeconomics (16)
Statistics (2)
Finance (2)
Energy Economics (11)

Partial List of GAMS Users

Texaco, Inc.
U.S. Department of Agriculture
Farmland Industries
Shearson Lehman Hutton
Hewlett-Packard Laboratories
J.P. Morgan Securities
NASA
Union Carbide
Johnson Wax
U.S. Department of Defense
U.S. Trust Company of New York
Apple Computers
Sumitomo Life Insurance Co.
Freihoferr A.G., Switzerland
The World Bank
Pacific Bell
McDonnel Douglas Corporation
U.S. Space Command
Air Force Institute of Technology
University of Arizona
University of California
Carnegie Mellon University
University of Connecticut
University of Florida
University of Haifa
Iowa State University
Kansas State University
Kyoto University
Louisiana State University
University of Maryland
University of Minnesota
University of Nebraska
University of New South Wales
North Dakota State University
Northwestern University
University of Notre Dame
Oklahoma State University
Old Dominion University
Oxford University
Purdue University
Rutgers University
University of Pennsylvania
Pennsylvania State University
University of San Francisco
University of South Carolina
Stanford University
SUNY, Utica
Syracuse University
University of Tennessee
University of Toronto
Utah State University
University of Valencia, Spain
Washington State University
University of Waterloo
University of Wisconsin, Madison
Yale University

The General Algebraic Modeling System(GAMS) simplifies the construction of models that are easily understood by the modeler and the computer. Such a modeling system:

1. **Provides a high-level language for the easy representation of large and complex models.**
2. **Simplifies making changes in the model.**
3. **Allows clear algebraic relationships to be made.**
4. **Separates the creation of a model from the solution technique or method that will be used on the model.**

The advantage of GAMS is that the person trying to solve the problem does not have to write all of the equations. All that is necessary is to specify what goes into the equations and the general form that they should take. The program does the actual equation writing.

—Chase and Aquilano, ***Production and Operations Management: A Life Cycle Approach****, 5th Edition*
Published by Irwin, 1989

GAMS in Action: An Example

This toy problem is presented to illustrate how GAMS lets you model in a natural way. GAMS can handle much larger and more complex problems. Only a few of the basic features of GAMS can be highlighted here.

1 Here is a standard algebraic description of the problem, which is to minimize the cost of shipping goods from 2 plants to 3 markets, subject to supply and demand constraints.

Indices:
- i = plants
- j = markets

Given Data:
- a_i = supply of commodity at plant i (cases)
- b_j = demand for commodity at market j (cases)
- c_{ij} = shipping cost per unit between plant i and market j ($/case/thousand miles)

	Markets			
	New York	Chicago	Topeka	
	(Distances, thousand miles)			*Supplies*
Plants				*(cases)*
Seattle	2.5	1.7	1.8	350
San Diego	2.5	1.8	1.4	600
Demands (cases)	325	300	275	

Cost = $90 per case per thousand miles

Decision Variables:
- x_{ij} = amount of commodity to ship from plant i to market j(cases), where $x_{ij} \geq 0$, for all i, j

Constraints:
- Supply limit at plant i (cases): $\sum_j x_{ij} \leq a_i$, for all i
- Demand at market j (cases): $\sum_i x_{ij} \geq b_j$, for all j

Objective Function:
- Minimize $\sum_i \sum_j c_{ij}$ (thousands of dollars)

2 The same problem modeled in GAMS. The use of concise algebraic descriptions makes the model highly compact, with a logical structure. Internal documentation, such as explanation of parameters and units of measurement, makes the model easy to read.

```
SETS
   I plants /SEATTLE, SAN-DIEGO/
   J markets /NEW-YORK, CHICAGO, TOPEKA/;

PARAMETERS
   A(I) capacity of plant i in cases
      /SEATTLE            350
      SAN-DIEGO           600/

   B(J) demand at market j in cases
      /NEW-YORK           325
      CHICAGO             300
      TOPEKA              275/;

TABLE D(I,J) distance in thousands of miles
            NEW-YORK  CHICAGO  TOPEKA
SEATTLE        2.5       1.7      1.8
SAN-DIEGO      2.5       1.8      1.4;

SCALAR F freight in dollars per case per
   thousand miles /90/;

PARAMETER
   C(I,J) transport cost in thousands of dollars
   per case; C(I,J) = F * D(I,J)/1000;

VARIABLES
   X(I,J) shipment quantities in cases
   Z  total transportation costs in thousands
   of dollars;

POSITIVE VARIABLE X;

EQUATIONS
   COST          define objective function
   SUPPLY(I)     observe supply limit at plant i
   DEMAND(J)     satisfy demand at market j;
COST..          Z = E = SUM ((I,J),
                C(I,J)*X(I,J));
SUPPLY(I)..     SUM(J,X(I,J)) =L= A(I);
DEMAND(J)..     SUM(I,X(I,J)) =G=B(J);

MODEL TRANSPORT / ALL /;

SOLVE TRANSPORT USING LP MINIMIZING Z;
```

GAMS lets you specify indices in a straightforward way, declare and name the sets (here I and J), and enumerate their elements.

Data can also be entered in convenient table form. GAMS lets you input data in their base form—transformations are specified algebraically.

A constant can simply be declared (as a "SCALAR") and its value specified.

When data values are to be calculated, you first declare the parameter (i.e., give it a symbol and, optionally, index it), then give its algebraic formulation. GAMS will automatically make the calculations.

Variables are specified as to type: FREE, POSITIVE, NEGATIVE, BINARY, or INTEGER.

Objective function and constraint equations are first declared by giving them names. Then their general algebraic formulae are described. GAMS now has enough information (from data entered above and from the algebraic relationships specified in the equations) to automatically generate each individual constraint statement—as you can see in the output report. An extensive set of tools enables you to model any expression that can be stated algebraically: arithmetic, indexing, functions, and exception-handling logic (e.g., if-then and such-that constructs).

Your "SOLVE" statement (1) tells GAMS which model to solve, (2) selects the solver to use (LP in this case),(3) indicates the direction of the solution, either "MINIMIZING" or "MAXIMIZING," and (4) specifies the objective value (here, Z).

Here data are entered as indexed parameters [A(I), B(J)], and values simply are listed.

GAMS lets you place explanatory text (shown in lower case) throughout your model, as you develop it. Your comments are automatically incorporated into the output report at the appropriate places.

Decision variables are expressed algebraically, with their indices specified. From this general form, GAMS generates each instance of the variable in the domain.

The objective variable (Z, here) is simply declared without an index.

"=E=" indicates "equal to"

"=L=" indicates "less than or equal to"

"=G=" indicates "greater than or equal to"

The model is given a unique name (here, "TRANSPORT"), and the modeler specifies which equations should be included in this particular formulation of the problem (in this case, "ALL" equations). This equation-selection feature enables you to formulate different models within a single GAMS input file, based on the same or different given data.

3 The GAMS output report (excerpts only). A full GAMS output report is much more extensive than the small excerpts shown here, and contains many aids for interpreting and diagnosing your model. Moreover, you can modify the output format to suit your particular purposes.

The basic model characteristics are reiterated.

GAMS tells you that an optimal solution has been found, and the optimized value is reported.

Constraint characteristics are listed. Explanatory comments from the original model are automatically integrated into the report, making the output easy to read at a glance.

The power of algebraic modeling: GAMS has taken the general equations and basic data from the modeler's work and generated specific statements for the objective function and constraints. This saves the modeler much time and effort—and reduces the potential for making errors in calculations and data entry.

Optimal levels for each decision variable are reported, along with upper and lower bounds and the marginal values.

```
              SOLVE SUMMARY

MODEL       TRANSPORT     OBJECTIVE     Z
TYPE        LP            DIRECTION     MINIMIZE
SOLVER      BDMLP         FROM LINE     49

****SOLVER STATUS      1 NORMAL COMPLETION
****MODEL STATUS       1 OPTIMAL
****OBJECTIVE VALUE                          153.6750

****EQU SUPPLY         OBSERVE SUPPLY LIMIT AT PLANT I
             LOWER     LOWER      LEVEL      UPPER
MARGINAL
SEATTLE      -INF       350.000    350.000    EPS
SAN-DIEGO    -INF       550.000    600.000     .

****EQU DEMAND          SATISFY DEMAND AT MARKET J
             LOWER      LEVEL      UPPER      MARGINAL
NEW-YORK     325.000    325.000    +INF        0.225
CHICAGO      300.000    300.000    +INF        0.153
TOPEKA       275.000    275.000    +INF        0.125

****COST     =E=  DEFINE OBJECTIVE FUNCTION

COST..-0.225*X(SEATTLE,NEW-YORK)  -0.153*X
        (SEATTLE,CHICAGO)
        -0.162*X(SEATTLE,TOPEKA) - 0.225*X
        (SAN-DIEGO,NEW-YORK)
        -0.162*X(SAN-DIEGO,CHICAGO) - 0.126*X
        (SAN-DIEGO,TOPEKA) +Z =E= 0 ;

****SUPPLY =L= OBSERVE SUPPLY LIMIT AT PLANT I

SUPPLY(SEATTLE)..  X(SEATTLE,NEW-YORK) +
        X(SEATTLE,CHICAGO)
        +X(SEATTLE,TOPEKA) =L= 350 ;
SUPPLY(SAN-DIEGO)..  X(SAN-DIEGO,NEW-YORK) +
        X(SAN-DIEGO,CHICAGO)
        + X(SAN-DIEGO,TOPEKA) =L= 600 ;

****DEMAND =G= SATISFY DEMAND AT MARKET J

DEMAND(NEW-YORK).. X(SEATTLE,NEW-YORK) +
        X (SAN-DIEGO, NEW-YORK) =G= 325 ;
DEMAND (CHICAGO)..  X(SEATTLE,CHICAGO) +
        X(SAN-DIEGO,CHICAGO)=G= 300 ;
DEMAND(TOPEKA)..  X(SEATTLE,TOPEKA) +
        X(SAN-DIEGO,TOPEKA) =G= 275

    VAR X   SHIPMENT QUANTITIES IN CASES
                         LOWER   LEVEL    UPPER    MARGINAL
SEATTLE . NEW YORK         .     50.000   +INF        .
SEATTLE . CHICAGO          .    300.000   +INF        .
SEATTLE . TOPEKA           .       .      +INF      0.036
SAN-DIEGO . NEW-YORK       .    275.000   +INF        .
SAN-DIEGO . CHICAGO        .       .      +INF      0.009
SAN-DIEGO . TOPEKA         .    275.000   +INF        .
```

Periods in tables indicate zeroes.

Sample GAMS input for the model used in this study

```
* Mixed Integer Programming Model for Maintenance Facilities Planning Study
*       Conducted for the Connecticut Department of Transportation
*             through the Joint Highway Research Program
*     Principal Investigators:  Gerard Campbell and Christian Davis

SET I   set of maintenance garages and other sources of equipment
  /GAR1 * GAR55, OTH1 * OTH21/;

SET F   set of repair facilities
  /WIN,BRO,DAR,WAT,MIL,EGR,WET,EHA,WWL,HIG,OSA,PUTN,LIS/;

SET E   set of equipment types
 /TYPE1A, TYPE1B, TYPE2, TYPE3, TYPE4, TYPE5/;

PARAMETER K(F)   annual fixed costs of facilities in thousands of dollars
 /WIN 191.6, BRO 281.4, DAR 236.5, WAT 202.6, MIL 208.8, EGR 217.2,
  WET 220.5, EHA 285.5, WWL 178.4, HIG 228.6, OSA 198.7, PUTN 184.2,
  LIS 268.8/;

PARAMETER P(F)   present capacity based on equipment servicable
 /WIN 120.48, BRO 89.16, DAR 141.36, WAT 78.72, MIL 141.36, EGR 120.48,
  WET 172.68, EHA 120.48, WWL 99.6, HIG 110.04, OSA 130.92, PUTN 110.04,
  LIS 120.48/;

SCALARS      ACAP    capacity added by two bays          /20.88/
             ACOST   cost of adding two bays             /22.15/
             BCAP    capacity added per bay above two    /10.44/
             BCOST   cost per bay above two              /8.075/;

TABLE G(I,E)  quantity of type e equipment at garage i
        TYPE1A  TYPE1B  TYPE2  TYPE3  TYPE4  TYPE5
GAR1       4       1      1      6      2     15
GAR2       4       1      1      4      5     13
GAR3       0       5     37     16     27     83
GAR4      10       9      9     24     15     52
GAR5       5       3      2      9     12     31
GAR6       2       2      1      1      8     11
GAR7       8       1      2     10      9     34
GAR8       6       4      3     14      9     42
GAR9       9       1      1     13      8     33
GAR10      6       7      1     15     19     42
GAR11      6       2      3     12     20     27
GAR12      8       8      1     19     12     35
GAR13      9       6      7     20     17     71
GAR14      5       3      2     12      7     28
GAR15     11       6     11     15     14     61
GAR16      9       4      2     16     13     32
GAR17      6       4      3     10     13     23
GAR18     10       2      1     13      5     32
GAR19     12       2      3     11      6     26
GAR20     11      18     34     32     49    237
GAR21     11       3      5     13     22     33
GAR22      6       3      1     13     10     27
GAR23      8       1      2     13      8     28
GAR24      8       3      2      8     20     31
GAR25     18       7      5     24     26     54
GAR26     11       0      1     14      5     31
GAR27     12       3      2     11     14     27
GAR28      9       2      3     11     17     23
GAR29      9       4      1      9     15     20
GAR30      7       1      7     13     13     35
GAR31      6       1      4      9      9     21
```

GAR32	2	2	0	5	8	6
GAR33	2	2	3	12	10	20
GAR34	12	3	2	15	19	34
GAR35	10	1	2	6	15	25
GAR36	6	8	5	17	26	41
GAR37	5	1	0	3	3	18
GAR38	8	3	8	16	11	43
GAR39	3	0	1	5	3	4
GAR40	9	3	1	9	8	27
GAR41	8	4	4	7	5	24
GAR42	8	3	1	8	11	27
GAR43	8	5	16	16	19	86
GAR44	13	1	3	12	13	43
GAR45	7	4	1	6	14	32
GAR46	7	3	3	9	16	47
GAR47	11	4	12	25	20	89
GAR48	6	3	3	12	13	38
GAR49	10	3	2	12	12	36
GAR50	9	4	2	9	12	44
GAR51	7	4	4	8	24	36
GAR52	6	3	1	8	7	37
GAR53	6	4	3	9	24	31
GAR54	7	5	7	20	14	60
GAR55	12	16	15	32	40	62
OTH1	0	3	2	8	10	8
OTH2	0	7	8	1	3	11
OTH3	0	1	6	1	4	17
OTH4	0	1	26	2	24	2
OTH5	0	1	12	6	4	34
OTH6	0	0	12	0	1	0
OTH7	0	2	16	1	8	6
OTH8	1	2	4	8	17	6
OTH9	0	12	29	23	38	120
OTH10	1	1	2	7	7	8
OTH11	0	3	7	15	21	53
OTH12	0	5	6	1	4	7
OTH13	1	4	17	3	12	12
OTH14	0	0	26	1	2	4
OTH15	1	0	31	5	7	7
OTH16	0	0	6	1	42	8
OTH17	0	0	15	0	3	7
OTH18	6	2	6	11	8	12
OTH19	0	2	6	15	2	10
OTH20	3	4	2	4	6	10
OTH21	0	0	17	0	3	6 ;

TABLE SUB(I,E) equipment subtracted from transportation costs

	TYPE1A	TYPE1B	TYPE2	TYPE3	TYPE4	TYPE5
GAR1	0	0	0	0	0	1
GAR2	0	0	0	0	0	4
GAR3	0	0	0	0	0	3
GAR4	0	0	0	0	0	4
GAR5	0	0	0	0	0	1
GAR6	0	0	0	0	0	2
GAR7	0	0	0	1	0	1
GAR8	0	0	0	0	0	1
GAR9	0	0	0	0	0	2
GAR10	0	0	0	0	0	5
GAR11	0	0	0	0	0	2
GAR12	0	0	0	1	0	3
GAR13	0	0	0	1	0	2
GAR14	0	0	0	0	0	0
GAR15	0	0	0	0	0	5
GAR16	0	0	0	0	0	3
GAR17	0	0	0	0	0	1

GAR18	0	0	0	0	0	1
GAR19	0	0	0	0	0	2
GAR20	0	0	0	4	0	13
GAR21	0	0	0	0	0	2
GAR22	0	0	0	0	0	1
GAR23	0	0	0	0	0	1
GAR24	0	0	0	0	0	1
GAR25	0	0	0	1	0	5
GAR26	0	0	0	0	0	1
GAR27	0	0	0	1	0	2
GAR28	0	0	0	0	0	1
GAR29	0	0	0	0	0	2
GAR30	0	0	0	0	0	2
GAR31	0	0	0	0	0	1
GAR32	0	0	0	0	0	0
GAR33	0	0	0	0	0	1
GAR34	0	0	0	0	0	2
GAR35	0	0	0	0	0	1
GAR36	0	0	0	1	0	4
GAR37	0	0	0	0	0	1
GAR38	0	0	0	0	0	1
GAR39	0	0	0	0	0	1
GAR40	0	0	0	0	0	1
GAR41	0	0	0	0	0	1
GAR42	0	0	0	1	0	1
GAR43	0	0	0	0	0	2
GAR44	0	0	0	0	0	2
GAR45	0	0	0	0	0	1
GAR46	0	0	0	0	0	3
GAR47	0	0	0	0	0	4
GAR48	0	0	0	0	0	1
GAR49	0	0	0	1	0	0
GAR50	0	0	0	0	0	1
GAR51	0	0	0	1	0	3
GAR52	0	0	0	0	0	1
GAR53	0	0	0	0	0	1
GAR54	0	0	0	0	0	3
GAR55	0	0	0	0	0	0
OTH1	0	0	0	0	0	0
OTH2	0	0	0	0	0	7
OTH3	0	0	0	0	0	0
OTH4	0	0	0	0	0	1
OTH5	0	0	0	0	0	0
OTH6	0	0	0	0	0	7
OTH7	0	0	0	0	0	1
OTH8	0	0	0	0	0	0
OTH9	0	0	0	1	0	2
OTH10	0	0	0	0	0	1
OTH11	0	0	0	1	0	2
OTH12	0	0	0	0	0	5
OTH13	0	0	0	0	0	2
OTH14	0	0	0	0	0	0
OTH15	0	0	0	0	0	0
OTH16	0	0	0	0	0	0
OTH17	0	0	0	0	0	0
OTH18	0	0	0	0	0	2
OTH19	0	0	0	0	0	0
OTH20	0	0	0	0	0	0
OTH21	0	0	0	0	0	0

TABLE DIST(I,F) distance between facility f and garage i

	WIN	BRO	DAR	WAT	MIL	EGR	WET
GAR1	15.13	9999	9999	35.60	9999	34.75	9999
GAR2	8.39	9999	9999	28.64	9999	28.01	37.86
GAR3	3.8	32.93	9999	16.6	9999	24.46	30.36

GAR4	0	9999	9999	24.00	9999	19.62	29.47
GAR5	16.0	28.04	9999	23.91	9999	36.89	9999
GAR6	23.01	25.58	9999	27.09	9999	9999	9999
GAR7	14.0	22.12	9999	14.85	9999	33.5	30.88
GAR8	33.33	6.0	38.26	26.5	9999	9999	9999
GAR9	31.07	16.54	9999	12.5	26.04	9999	32.21
GAR10	9999	6.0	27.33	26.92	27.39	9999	9999
GAR11	9999	26.42	5.03	9999	23.56	9999	9999
GAR12	9999	31.26	0	9999	26.71	9999	9999
GAR13	9999	25.14	8.4	9999	18.46	9999	9999
GAR14	9999	27.15	14.74	34.2	11.43	9999	9999
GAR15	24.0	28.55	9999	0	27.86	34.69	23.02
GAR16	18.71	28.9	9999	5.29	33.15	30.72	19.05
GAR17	29.79	34.58	9999	13.13	27.61	29.31	14.92
GAR18	36.28	23.51	36.69	12.28	15.61	9999	31.66
GAR19	9999	23.41	31.24	21.94	5.79	9999	33.19
GAR20	9999	29.02	26.17	27.86	0	9999	38.01
GAR21	9999	25.99	21.56	29.43	5.35	9999	9999
GAR22	9999	38.21	9999	32.93	16.34	9999	28.9
GAR23	9999	29.67	32.83	25.04	6.73	9999	32.23
GAR24	9999	34.65	9999	21.6	15.71	9999	22.59
GAR25	42.07	39.19	9999	22.29	20.63	38.39	18.33
GAR26	20.28	9999	9999	17.41	38.84	17.57	9.19
GAR27	29.04	9999	9999	31.05	9999	17.7	8.5
GAR28	29.75	9999	9999	30.62	9999	18.41	7.6
GAR29	35.34	41.53	9999	20.08	26.41	31.66	11.6
GAR30	34.91	40.1	9999	19.65	28.68	29.09	9.26
GAR31	15.67	9999	9999	23.49	9999	11.49	15.27
GAR32	19.15	9999	9999	29.45	9999	5.24	19.89
GAR33	19.62	9999	9999	34.69	9999	0	20.35
GAR34	26.58	9999	9999	37.43	9999	6.96	18.21
GAR35	27.28	9999	9999	32.27	9999	7.66	13.05
GAR36	34.29	9999	9999	36.30	9999	17.39	15.43
GAR37	9999	9999	9999	9999	9999	30.29	33.84
GAR38	9999	9999	9999	9999	9999	29.22	28.52
GAR39	9999	9999	9999	9999	9999	38.83	31.31
GAR40	35.52	9999	9999	37.53	9999	24.18	16.66
GAR41	9999	9999	9999	28.36	33.5	31.16	14.76
GAR42	9999	9999	9999	38.68	9999	27.60	16.79
GAR43	9999	9999	9999	9999	9999	33.88	23.07
GAR44	9999	9999	9999	37.94	39.49	9999	24.34
GAR45	9999	9999	9999	38.59	22.03	9999	32.27
GAR46	9999	9999	9999	9999	9999	9999	39.69
GAR47	9999	9999	9999	9999	37.55	9999	35.05
GAR48	9999	9999	9999	9999	9999	9999	35.0
GAR49	9999	9999	9999	9999	9999	9999	9999
GAR50	9999	9999	9999	9999	9999	9999	9999
GAR51	9999	9999	9999	9999	9999	9999	39.77
GAR52	9999	9999	9999	9999	9999	9999	9999
GAR53	9999	9999	9999	9999	9999	9999	9999
GAR54	9999	9999	9999	9999	9999	9999	9999
GAR55	29.47	9999	9999	23.02	9999	20.35	0
OTH1	36.55	17.82	9999	12.55	18.92	9999	31.93
OTH2	29.14	31.93	9999	10.48	31.24	29.68	17.3
OTH3	9999	31.28	38.14	22.89	12.69	9999	25.32
OTH4	9999	31.28	38.14	22.89	12.69	9999	25.32
OTH5	28.63	9999	9999	31.01	9999	19.49	4.59
OTH6	25.26	9999	9999	27.27	9999	13.92	7.19
OTH7	9999	9999	9999	31.05	9999	17.7	10.18
OTH8	27.5	9999	9999	29.5	9999	15.2	4.2
OTH9	25.26	9999	9999	27.27	9999	13.92	7.19
OTH10	9999	9999	9999	9999	9999	9999	9999
OTH11	9999	9999	9999	9999	34.44	9999	35.98
OTH12	9999	9999	9999	9999	9999	9999	9999
OTH13	9999	9999	9999	9999	9999	9999	9999

OTH14	29.37	9999	9999	21.38	9999	21.99	1.64
OTH15	33.38	9999	9999	29.05	9999	22.06	6.57
OTH16	29.47	9999	9999	23.02	9999	20.35	0
OTH17	33.38	9999	9999	29.05	9999	22.06	6.57
OTH18	9999	9999	9999	9999	9999	9999	34.33
OTH19	9999	9999	9999	29.12	33.31	30.24	14.0
OTH20	9999	9999	9999	9999	9999	9999	9999
OTH21	9999	9999	9999	9999	9999	9999	39.75

+	EHA	WWL	HIG	OSA	PUTN	LIS
GAR1	9999	9999	9999	9999	9999	9999
GAR2	9999	9999	9999	9999	9999	9999
GAR3	9999	9999	9999	9999	9999	9999
GAR4	9999	9999	9999	9999	9999	9999
GAR5	9999	9999	9999	9999	9999	9999
GAR6	9999	9999	9999	9999	9999	9999
GAR7	9999	9999	9999	9999	9999	9999
GAR8	9999	9999	9999	9999	9999	9999
GAR9	29.77	9999	38.00	9999	9999	9999
GAR10	33.85	9999	9999	9999	9999	9999
GAR11	37.1	9999	9999	9999	9999	9999
GAR12	9999	9999	9999	9999	9999	9999
GAR13	32.45	9999	9999	9999	9999	9999
GAR14	24.97	9999	9999	9999	9999	9999
GAR15	28.46	9999	32.63	9999	9999	9999
GAR16	33.75	9999	33.48	9999	9999	9999
GAR17	20.49	9999	20.52	37.2	9999	9999
GAR18	17.95	9999	33.18	9999	9999	9999
GAR19	12.32	9999	34.22	36.67	9999	9999
GAR20	13.61	9999	39.07	38.21	9999	9999
GAR21	18.89	9999	9999	9999	9999	9999
GAR22	6.92	9999	29.9	21.87	9999	9999
GAR23	6.88	9999	32.34	31.48	9999	9999
GAR24	7.52	9999	23.24	31.47	9999	9999
GAR25	11.3	9999	18.44	30.12	9999	9999
GAR26	31.72	32.77	26.47	9999	9999	9999
GAR27	39.52	18.34	25.26	9999	9999	35.44
GAR28	33.34	25.37	18.35	35.03	9999	34.40
GAR29	18.03	39.83	13.79	30.47	9999	9999
GAR30	20.37	37.26	14.89	31.57	9999	9999
GAR31	37.80	31.71	31.1	9999	9999	9999
GAR32	9999	33.59	34.97	9999	9999	9999
GAR33	9999	29.22	35.43	9999	9999	9999
GAR34	9999	23.52	33.29	9999	9999	9999
GAR35	9999	25.18	28.13	9999	9999	9999
GAR36	9999	13.09	30.51	9999	36.26	33.92
GAR37	9999	7.25	9999	9999	22.51	32.69
GAR38	9999	0	42.48	9999	23.17	27.7
GAR39	9999	12.94	30.76	35.39	24.44	16.21
GAR40	9999	15.03	31.74	9999	34.49	28.96
GAR41	21.9	39.33	4.27	20.95	9999	37.19
GAR42	37.87	24.64	19.51	26.84	38.73	25.21
GAR43	39.77	26.62	18.66	23.58	9999	18.93
GAR44	26.6	38.21	5.49	11.96	9999	29.79
GAR45	10.27	9999	23.26	17.27	9999	9999
GAR46	39.2	36.71	28.91	13.75	9999	14.2
GAR47	25.79	9999	16.7	0.66	9999	27.61
GAR48	9999	25.39	28.28	27.25	30.41	7.0
GAR49	9999	26.78	34.36	28.77	25.65	0.92
GAR50	9999	9999	39.26	24.1	36.14	16.43
GAR51	9999	27.98	33.05	22.48	31.31	7.21
GAR52	9999	25.3	9999	39.81	16.34	11.91
GAR53	9999	16.05	9999	9999	8.35	23.18
GAR54	9999	23.17	9999	9999	0	25.44
GAR55	29.63	28.52	19.03	35.71	9999	9999

OTH1	22.65	9999	38.08	9999	9999	9999
OTH2	26.17	9999	26.68	9999	9999	9999
OTH3	9.42	9999	26.35	35.74	9999	9999
OTH4	9.42	9999	26.35	35.74	9999	9999
OTH5	30.20	27.66	15.94	32.63	9999	39.54
OTH6	36.53	22.12	22.27	38.75	9999	9999
OTH7	39.52	18.34	25.26	9999	9999	35.44
OTH8	9999	21.3	21.0	9999	9999	9999
OTH9	36.53	22.12	22.27	38.75	9999	9999
OTH10	9999	9999	35.52	20.36	9999	15.51
OTH11	22.68	9999	17.63	4.01	9999	31.68
OTH12	9999	9999	35.29	22.35	31.26	5.82
OTH13	9999	26.79	9999	9999	14.85	12.67
OTH14	29.48	30.16	18.88	9999	9999	9999
OTH15	28.24	30.23	13.51	9999	9999	9999
OTH16	29.63	28.52	19.03	35.74	9999	9999
OTH17	28.24	30.23	13.51	9999	9999	9999
OTH18	9999	12.5	27.96	36.4	28.02	20.0
OTH19	22.18	39.59	9.5	25.0	9999	36.24
OTH20	6.34	9999	26.05	10.89	9999	17.19
OTH21	9999	27.25	33.00	22.6	31.53	7.13

;

TABLE TIME(I,F) travel time between facility f and garage i

	WIN	BRO	DAR	WAT	MIL	EGR	WET
GAR1	0.33	9999	9999	0.72	9999	0.75	9999
GAR2	0.18	9999	9999	0.57	9999	0.60	0.82
GAR3	0.07	0.59	9999	0.29	9999	0.50	0.59
GAR4	0	9999	9999	0.43	9999	0.42	0.64
GAR5	0.33	0.62	9999	0.50	9999	0.77	9999
GAR6	0.48	0.57	9999	0.57	9999	9999	9999
GAR7	0.28	0.51	9999	0.31	9999	0.71	0.64
GAR8	0.71	0.14	1.08	0.66	9999	9999	9999
GAR9	0.61	0.35	9999	0.28	0.56	9999	0.63
GAR10	9999	0.14	0.80	0.49	0.70	9999	9999
GAR11	9999	0.57	0.1	9999	0.45	9999	9999
GAR12	9999	0.66	0.00	9999	0.47	9999	9999
GAR13	9999	0.55	0.15	9999	0.35	9999	9999
GAR14	9999	0.59	0.26	0.61	0.21	9999	9999
GAR15	0.43	0.53	9999	0.00	0.54	0.75	0.46
GAR16	0.34	0.62	9999	0.09	0.63	0.68	0.39
GAR17	0.64	0.65	9999	0.24	0.56	0.63	0.28
GAR18	0.64	0.46	0.66	0.21	0.33	0.92	0.57
GAR19	9999	0.49	0.57	0.41	0.13	9999	0.65
GAR20	9999	0.64	0.47	0.54	0.00	9999	0.74
GAR21	9999	0.58	0.39	0.55	0.10	9999	9999
GAR22	9999	0.80	9999	0.63	0.31	9999	0.62
GAR23	9999	0.63	0.59	0.48	0.13	9999	0.63
GAR24	9999	0.69	9999	0.44	0.30	9999	0.45
GAR25	0.89	0.78	9999	0.46	0.38	0.68	0.38
GAR26	0.45	0.85	9999	0.37	0.79	0.36	0.19
GAR27	0.64	9999	9999	0.63	9999	0.35	0.16
GAR28	0.65	9999	9999	0.61	9999	0.36	0.15
GAR29	0.73	0.77	9999	0.36	0.49	0.59	0.25
GAR30	0.75	0.76	9999	0.35	0.54	0.59	0.20
GAR31	0.35	9999	9999	0.51	9999	0.25	0.33
GAR32	0.41	9999	9999	0.64	9999	0.11	0.43
GAR33	0.42	9999	9999	0.75	9999	0.00	0.40
GAR34	0.56	9999	9999	0.74	9999	0.14	0.34
GAR35	0.59	9999	9999	0.65	9999	0.17	0.25
GAR36	0.73	9999	9999	0.72	9999	0.37	0.28
GAR37	9999	9999	9999	9999	9999	0.68	0.62
GAR38	9999	9999	9999	9999	9999	0.61	0.53
GAR39	9999	9999	9999	9999	9999	0.79	0.63
GAR40	0.75	9999	9999	0.74	9999	0.46	0.30
GAR41	9999	9999	9999	0.52	0.60	0.58	0.28

GAR42	9999	9999	9999	0.77	9999	0.52	0.31
GAR43	9999	9999	9999	9999	9999	0.64	0.43
GAR44	9999	9999	9999	0.73	0.82	9999	0.48
GAR45	9999	9999	9999	0.74	0.42	9999	0.69
GAR46	9999	9999	9999	9999	9999	9999	0.77
GAR47	9999	9999	9999	9999	0.69	9999	0.64
GAR48	9999	9999	9999	9999	9999	9999	0.64
GAR49	9999	9999	9999	9999	9999	9999	9999
GAR50	9999	9999	9999	9999	9999	9999	9999
GAR51	9999	9999	9999	9999	9999	9999	0.73
GAR52	9999	9999	9999	9999	9999	9999	9999
GAR53	9999	9999	9999	9999	9999	9999	9999
GAR54	9999	9999	9999	9999	9999	9999	9999
GAR55	0.64	9999	9999	0.46	9999	0.40	0.00
OTH1	0.67	0.34	9999	0.24	0.41	9999	0.60
OTH2	0.58	0.61	9999	0.20	0.62	0.65	0.35
OTH3	9999	0.64	0.68	0.47	0.24	9999	0.50
OTH4	9999	0.64	0.68	0.47	0.24	9999	0.50
OTH5	0.64	9999	9999	0.55	9999	0.38	0.10
OTH6	0.57	9999	9999	0.56	9999	0.28	0.13
OTH7	9999	9999	9999	0.63	9999	0.35	0.19
OTH8	0.59	9999	9999	0.64	9999	0.32	0.09
OTH9	0.57	9999	9999	0.56	9999	0.28	0.13
OTH10	9999	9999	9999	9999	9999	9999	9999
OTH11	9999	9999	9999	9999	0.64	9999	0.68
OTH12	9999	9999	9999	9999	9999	9999	9999
OTH13	9999	9999	9999	9999	9999	9999	9999
OTH14	0.62	9999	9999	0.43	9999	0.43	0.03
OTH15	0.71	9999	9999	0.52	9999	0.42	0.13
OTH16	0.64	9999	9999	0.46	9999	0.40	0.00
OTH17	0.71	9999	9999	0.52	9999	0.42	0.13
OTH18	9999	9999	9999	9999	9999	9999	0.69
OTH19	9999	9999	9999	0.53	0.61	0.56	0.25
OTH20	9999	9999	9999	9999	9999	9999	9999
OTH21	9999	9999	9999	9999	9999	9999	0.74

+	EHA	WWL	HIG	OSA	PUTN	LIS
GAR1	9999	9999	9999	9999	9999	9999
GAR2	9999	9999	9999	9999	9999	9999
GAR3	9999	9999	9999	9999	9999	9999
GAR4	9999	9999	9999	9999	9999	9999
GAR5	9999	9999	9999	9999	9999	9999
GAR6	9999	9999	9999	9999	9999	9999
GAR7	9999	9999	9999	9999	9999	9999
GAR8	9999	9999	9999	9999	9999	9999
GAR9	0.61	9999	0.75	9999	9999	9999
GAR10	0.70	9999	9999	9999	9999	9999
GAR11	0.69	9999	9999	9999	9999	9999
GAR12	9999	9999	9999	9999	9999	9999
GAR13	0.59	9999	9999	9999	9999	9999
GAR14	0.45	9999	9999	9999	9999	9999
GAR15	0.57	9999	0.61	9999	9999	9999
GAR16	0.66	9999	0.65	9999	9999	9999
GAR17	0.42	9999	0.41	0.68	9999	9999
GAR18	0.36	9999	0.68	0.82	9999	9999
GAR19	0.25	9999	0.69	0.71	9999	9999
GAR20	0.25	9999	0.78	0.71	9999	9999
GAR21	0.34	9999	9999	9999	9999	9999
GAR22	0.14	9999	0.64	0.40	9999	9999
GAR23	0.12	9999	0.65	0.58	9999	9999
GAR24	0.14	9999	0.49	0.62	9999	9999
GAR25	0.21	9999	0.40	0.60	9999	9999
GAR26	0.65	0.62	0.50	9999	9999	9999
GAR27	0.72	0.34	0.46	9999	9999	0.77
GAR28	0.65	0.47	0.38	0.68	9999	0.63

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GAR29  0.34   0.72   0.27   0.57   9999   9999
GAR30  0.39   0.72   0.30   0.60   9999   9999
GAR31  0.79   0.63   0.61   9999   9999   9999
GAR32  9999   0.68   0.70   9999   9999   9999
GAR33  9999   0.62   0.67   9999   9999   9999
GAR34  9999   0.48   0.61   9999   9999   9999
GAR35  9999   0.51   0.52   9999   9999   9999
GAR36  9999   0.25   0.55   9999   0.75   0.76
GAR37  9999   0.14   9999   9999   0.50   0.72
GAR38  9999   0      9999   9999   0.50   0.60
GAR39  9999   0.28   0.67   0.74   0.50   0.36
GAR40  9999   0.30   0.57   9999   0.75   0.66
GAR41  0.49   0.71   0.09   0.39   9999   0.75
GAR42  0.77   0.54   0.42   0.53   0.85   0.47
GAR43  0.87   0.59   0.41   0.46   9999   0.35
GAR44  0.58   0.76   0.12   0.26   9999   0.60
GAR45  0.22   9999   0.48   0.32   9999   9999
GAR46  0.73   0.76   0.52   0.25   9999   0.30
GAR47  0.49   9999   0.31   0.02   9999   0.54
GAR48  9999   0.54   0.58   0.51   0.54   0.14
GAR49  9999   0.58   0.70   0.53   0.45   0.02
GAR50  9999   9999   0.73   0.46   0.72   0.37
GAR51  9999   0.59   0.67   0.42   0.56   0.15
GAR52  9999   0.55   9999   0.77   0.30   0.26
GAR53  9999   0.35   9999   9999   0.17   0.50
GAR54  9999   0.50   9999   9999   0.00   0.46
GAR55  0.59   0.53   0.36   0.66   9999   9999
OTH1   0.46   9999   0.73   9999   9999   9999
OTH2   0.54   9999   0.53   9999   9999   9999
OTH3   0.17   9999   0.54   0.68   9999   9999
OTH4   0.17   9999   0.54   0.68   9999   9999
OTH5   0.55   0.51   0.29   0.59   9999   0.73
OTH6   0.66   0.41   0.40   0.70   9999   9999
OTH7   0.72   0.34   0.46   9999   9999   0.77
OTH8   9999   0.43   0.42   9999   9999   9999
OTH9   0.66   0.41   0.40   0.70   9999   9999
OTH10  9999   9999   0.64   0.37   9999   0.35
OTH11  0.44   9999   0.35   0.09   9999   0.61
OTH12  9999   9999   0.69   0.42   0.59   0.13
OTH13  9999   0.59   9999   9999   0.26   0.24
OTH14  0.59   0.56   0.36   9999   9999   9999
OTH15  0.52   0.55   0.25   9999   9999   9999
OTH16  0.59   0.53   0.36   0.66   9999   9999
OTH17  0.52   0.55   0.25   9999   9999   9999
OTH18  9999   0.26   0.62   0.77   0.61   0.46
OTH19  0.47   0.73   0.23   0.44   9999   0.76
OTH20  0.68   9999   0.47   0.20   9999   0.36
OTH21  9999   0.57   0.66   0.42   0.54   0.14   ;

PARAMETER W(E)  weight for equipment type e based on work bays
 /TYPE1A 1, TYPE1B .59, TYPE2 .33, TYPE3 .38, TYPE4 0, TYPE5 0/;

PARAMETER DEM(I)   total weighted demand at garage i;
 DEM(I) = SUM( E, ( W(E)*G(I,E) ));

PARAMETER CALL(E)   identifier for equipment types
 /TYPE1A 1, TYPE1B 10, TYPE2 2, TYPE3 3, TYPE4 4, TYPE5 5/;

PARAMETER DCHECK(F,I,E)  special identifier for type 3 equipment;

DCHECK(F,I,E)$(CALL(E) EQ 3) = 1$(DIST(I,F) LE 9.17) + 2$(DIST(I,F) GT 9.17) ;
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PARAMETER PARTC(F,I,E)  partial annual transportation costs;

PARTC(F,I,E)$(CALL(E) EQ 1) = (DIST(I,F)*1.09*4.68
   + TIME(I,F)*1.09*250.72)*9.4*G(I,E)/1000 ;

PARTC(F,I,E)$(CALL(E) EQ 10) = (DIST(I,F)*1.09*6.00
   + TIME(I,F)*1.09*250.72)*9.4*G(I,E)/1000 ;

PARTC(F,I,E)$(CALL(E) EQ 2) = (DIST(I,F)*1.09*3.56
   + TIME(I,F)*1.09*263.16)*5.2*G(I,E)/1000 ;

PARTC(F,I,E)$(DCHECK(F,I,E) EQ 1) = (DIST(I,F)*1.09*5.56
   + TIME(I,F)*1.09*398.16)*3.4*(G(I,E)-SUB(I,E))/1000 ;

PARTC(F,I,E)$(DCHECK(F,I,E) EQ 2) = (68.20 + DIST(I,F)*1.09*10.24
   + TIME(I,F)*1.09*136.40)*3.4*(G(I,E)-SUB(I,E))/1000;

PARTC(F,I,E)$(CALL(E) EQ 4) = (DIST(I,F)*1.09*2.00
   + TIME(I,F)*1.09*131.60)*1.4*G(I,E)/1000 ;

PARTC(F,I,E)$(CALL(E) EQ 5) = (DIST(I,F)*1.09*2.00
   + TIME(I,F)*1.09*131.60)*0.7*(G(I,E)-SUB(I,E))/1000  ;

PARAMETER C(F,I)   annual transportation costs in thousands of dollars;

C(F,I) = SUM(E,PARTC(F,I,E)) + (DIST(I,F)*1.09*1.00
         + TIME(I,F)*1.09*65.80)*26/1000 ;

VARIABLES
   A(F)      binary variable indicating if two bays are added
   B(F)      number of bays added above two
   X(F,I)    shipment percentages
   Y(F)      binary variable indicating if facility is kept open
   Z         total cost;

POSITIVE VARIABLE X;

POSITIVE VARIABLE B;

BINARY VARIABLE A;

BINARY VARIABLE Y;

EQUATIONS
   COST            objective function
   DEMAND(I)       all of garage i demand must be met
   SUPPLY(F)       capacity of facility f cannot be exceeded
   EXPAND1(F)      first expansion not allowed unless facility is open
   EXPAND2(F)      additional expansions not allowed without first
   TIGHTEN(F,I)    extra constraints added to tighten l.p. bounds
   TOTFAC          constraint on total number of facilities ;

COST ..   Z =E= SUM(F,(K(F)*Y(F)+ACOST*A(F)+BCOST*B(F)))
           +SUM((F,I)$(DIST(I,F) LE 40),C(F,I)*X(F,I));

DEMAND(I)..   SUM(F$(DIST(I,F) LE 40),X(F,I)) =E= 1;

SUPPLY(F)..  SUM(I$(DIST(I,F) LE 40),(DEM(I)*X(F,I))) =L=
             P(F)*Y(F)+ACAP*A(F)+BCAP*B(F);

EXPAND1(F).. A(F) =L= Y(F);

EXPAND2(F).. B(F) =L= 8*A(F);
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TIGHTEN(F,I)$(DIST(I,F) LT 20)..   X(F,I) =L= Y(F);

TOTFAC ..  SUM(F,Y(F)) =L= 13 ;

MODEL CONNDOT /ALL/;

SOLVE CONNDOT USING MIP MINIMIZING Z;

DISPLAY X.L, Y.L, A.L, B.L;
```

<u>Sample GAMS output from the model used in this study</u>

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---- COST        =E=  OBJECTIVE FUNCTION

COST..  - 22.15*A(WIN) - 22.15*A(BRO) - 22.15*A(DAR) - 22.15*A(WAT)

      - 22.15*A(MIL) - 22.15*A(EGR) - 22.15*A(WET) - 22.15*A(EHA)

      - 22.15*A(WWL) - 22.15*A(HIG) - 22.15*A(OSA) - 22.15*A(PUTN)

      - 22.15*A(LIS) - 8.075*B(WIN) - 8.075*B(BRO) - 8.075*B(DAR)

      - 8.075*B(WAT) - 8.075*B(MIL) - 8.075*B(EGR) - 8.075*B(WET)

      - 8.075*B(EHA) - 8.075*B(WWL) - 8.075*B(HIG) - 8.075*B(OSA)

      - 8.075*B(PUTN) - 8.075*B(LIS) - 16.7617*X(WIN,GAR1) - 7.7888*X(WIN,GAR2)

      - 13.63*X(WIN,GAR3) - 28.4285*X(WIN,GAR5) - 16.126*X(WIN,GAR6)

      - 25.6898*X(WIN,GAR7) - 76.6735*X(WIN,GAR8) - 62.002*X(WIN,GAR9)

      - 81.2581*X(WIN,GAR15) - 48.232*X(WIN,GAR16) - 61.1678*X(WIN,GAR17)

      - 75.518*X(WIN,GAR18) - 46.1581*X(WIN,GAR26) - 74.1538*X(WIN,GAR27)

      - 66.4102*X(WIN,GAR28) - 76.0703*X(WIN,GAR29) - 77.1789*X(WIN,GAR30)

      - 27.4906*X(WIN,GAR31) - 17.0892*X(WIN,GAR32) - 30.0934*X(WIN,GAR33)

      - 75.9462*X(WIN,GAR34) - 51.0039*X(WIN,GAR35) - 105.8361*X(WIN,GAR36)

      - 72.3107*X(WIN,GAR40) - 186.3184*X(WIN,GAR55) - 36.7696*X(WIN,OTH1)

      - 39.1598*X(WIN,OTH2) - 38.1821*X(WIN,OTH5) - 17.6187*X(WIN,OTH6)

      - 33.5042*X(WIN,OTH8) - 128.5328*X(WIN,OTH9) - 43.9578*X(WIN,OTH14)

      - 71.2588*X(WIN,OTH15) - 23.0475*X(WIN,OTH16) - 29.8476*X(WIN,OTH17)

      - 120.0292*X(BRO,GAR3) - 49.7246*X(BRO,GAR5) - 18.5071*X(BRO,GAR6)

      - 41.9238*X(BRO,GAR7) - 14.2115*X(BRO,GAR8) - 35.4355*X(BRO,GAR9)

      - 16.4388*X(BRO,GAR10) - 53.1378*X(BRO,GAR11) - 96.1399*X(BRO,GAR12)

      - 89.8022*X(BRO,GAR13) - 51.3208*X(BRO,GAR14) - 97.4446*X(BRO,GAR15)

      - 77.397*X(BRO,GAR16) - 66.7372*X(BRO,GAR17) - 52.0292*X(BRO,GAR18)

      - 57.2632*X(BRO,GAR19) - 230.8198*X(BRO,GAR20) - 75.1175*X(BRO,GAR21)
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- 74.5747*X(BRO,GAR22) - 59.3226*X(BRO,GAR23) - 68.6218*X(BRO,GAR24)

- 175.6788*X(BRO,GAR25) - 19.1366*X(BRO,OTH1) - 42.037*X(BRO,OTH2)

- 19.7041*X(BRO,OTH3) - 55.8502*X(BRO,OTH4) - 99.4665*X(DAR,GAR8)

- 84.6056*X(DAR,GAR10) - 9.3677*X(DAR,GAR11) - 26.1396*X(DAR,GAR13)

- 26.9822*X(DAR,GAR14) - 76.9103*X(DAR,GAR18) - 71.2443*X(DAR,GAR19)

- 190.1924*X(DAR,GAR20) - 57.4149*X(DAR,GAR21) - 61.1582*X(DAR,GAR23)

- 22.3287*X(DAR,OTH3) - 63.0648*X(DAR,OTH4) - 36.3688*X(WAT,GAR1)

- 26.2233*X(WAT,GAR2) - 61.6681*X(WAT,GAR3) - 96.253*X(WAT,GAR4)

- 41.6936*X(WAT,GAR5) - 19.0257*X(WAT,GAR6) - 27.6121*X(WAT,GAR7)

- 65.9268*X(WAT,GAR8) - 28.1413*X(WAT,GAR9) - 67.9328*X(WAT,GAR10)

- 59.1716*X(WAT,GAR14) - 12.199*X(WAT,GAR16) - 26.4933*X(WAT,GAR17)

- 27.258*X(WAT,GAR18) - 51.2932*X(WAT,GAR19) - 208.9368*X(WAT,GAR20)

- 78.3201*X(WAT,GAR21) - 62.4469*X(WAT,GAR22) - 48.5273*X(WAT,GAR23)

- 43.912*X(WAT,GAR24) - 103.7797*X(WAT,GAR25) - 39.3884*X(WAT,GAR26)

- 76.207*X(WAT,GAR27) - 65.5762*X(WAT,GAR28) - 41.5973*X(WAT,GAR29)

- 41.4873*X(WAT,GAR30) - 39.6669*X(WAT,GAR31) - 25.8172*X(WAT,GAR32)

- 51.2676*X(WAT,GAR33) - 102.7098*X(WAT,GAR34) - 58.0873*X(WAT,GAR35)

- 108.533*X(WAT,GAR36) - 74.0322*X(WAT,GAR40) - 55.1958*X(WAT,GAR41)

- 69.3586*X(WAT,GAR42) - 93.5151*X(WAT,GAR44) - 67.99*X(WAT,GAR45)

- 142.1089*X(WAT,GAR55) - 14.0365*X(WAT,OTH1) - 13.946*X(WAT,OTH2)

- 14.5085*X(WAT,OTH3) - 41.076*X(WAT,OTH4) - 37.0041*X(WAT,OTH5)

- 17.9544*X(WAT,OTH6) - 38.2211*X(WAT,OTH7) - 35.9733*X(WAT,OTH8)

- 132.4565*X(WAT,OTH9) - 31.1674*X(WAT,OTH14) - 56.7508*X(WAT,OTH15)

- 17.2332*X(WAT,OTH16) - 23.475*X(WAT,OTH17) - 41.8261*X(WAT,OTH19)

- 54.4189*X(MIL,GAR9) - 79.5061*X(MIL,GAR10) - 45.385*X(MIL,GAR11)

- 77.1948*X(MIL,GAR12) - 63.2989*X(MIL,GAR13) - 21.8472*X(MIL,GAR14)

- 96.9518*X(MIL,GAR15) - 84.024*X(MIL,GAR16) - 55.4715*X(MIL,GAR17)

- 36.6615*X(MIL,GAR18) - 14.2681*X(MIL,GAR19) - 13.7455*X(MIL,GAR21)

- 32.4068*X(MIL,GAR22) - 12.393*X(MIL,GAR23) - 31.5593*X(MIL,GAR24)

- 92.0883*X(MIL,GAR25) - 82.3625*X(MIL,GAR26) - 54.8141*X(MIL,GAR29)

- 60.4897*X(MIL,GAR30) - 64.2571*X(MIL,GAR41) - 100.5375*X(MIL,GAR44)

- 39.3115*X(MIL,GAR45) - 145.3863*X(MIL,GAR47) - 21.1547*X(MIL,OTH1)

- 41.9053*X(MIL,OTH2) - 7.8095*X(MIL,OTH3) - 21.9682*X(MIL,OTH4)

- 61.9377*X(MIL,OTH11) - 47.4372*X(MIL,OTH19) - 36.5266*X(EGR,GAR1)

- 26.5232*X(EGR,GAR2) - 95.7574*X(EGR,GAR3) - 85.4586*X(EGR,GAR4)

- 63.1442*X(EGR,GAR5) - 60.0707*X(EGR,GAR7) - 125.9182*X(EGR,GAR15)

- 83.1241*X(EGR,GAR16) - 60.2326*X(EGR,GAR17) - 164.1878*X(EGR,GAR25)

- 39.1483*X(EGR,GAR26) - 43.9478*X(EGR,GAR27) - 40.1349*X(EGR,GAR28)

- 65.4153*X(EGR,GAR29) - 63.2289*X(EGR,GAR30) - 20.4873*X(EGR,GAR31)

- 4.4011*X(EGR,GAR32) - 18.8174*X(EGR,GAR34) - 14.3032*X(EGR,GAR35)

- 55.4893*X(EGR,GAR36) - 29.5407*X(EGR,GAR37) - 80.9563*X(EGR,GAR38)

- 27.9808*X(EGR,GAR39) - 47.7198*X(EGR,GAR40) - 60.8792*X(EGR,GAR41)

- 48.7791*X(EGR,GAR42) - 116.755*X(EGR,GAR43) - 125.6455*X(EGR,GAR55)

- 41.8536*X(EGR,OTH2) - 24.7895*X(EGR,OTH5) - 9.0521*X(EGR,OTH6)

- 21.5818*X(EGR,OTH7) - 19.2042*X(EGR,OTH8) - 69.4863*X(EGR,OTH9)

- 31.5353*X(EGR,OTH14) - 44.7639*X(EGR,OTH15) - 15.1246*X(EGR,OTH16)

- 18.4682*X(EGR,OTH17) - 43.5409*X(EGR,OTH19) - 35.7055*X(WET,GAR2)

- 115.1616*X(WET,GAR3) - 126.3368*X(WET,GAR4) - 54.9912*X(WET,GAR7)

- 64.0703*X(WET,GAR9) - 81.7898*X(WET,GAR15) - 51.3133*X(WET,GAR16)

- 30.0941*X(WET,GAR17) - 66.8012*X(WET,GAR18) - 77.8189*X(WET,GAR19)

- 283.2585*X(WET,GAR20) - 57.7009*X(WET,GAR22) - 62.0689*X(WET,GAR23)

- 45.3904*X(WET,GAR24) - 86.4541*X(WET,GAR25) - 22.0975*X(WET,GAR26)

- 19.6349*X(WET,GAR27) - 15.7296*X(WET,GAR28) - 26.8502*X(WET,GAR29)

- 22.7349*X(WET,GAR30) - 26.4639*X(WET,GAR31) - 17.7749*X(WET,GAR32)

- 30.162*X(WET,GAR33) - 50.5944*X(WET,GAR34) - 23.7847*X(WET,GAR35)

- 46.6438*X(WET,GAR36) - 29.9732*X(WET,GAR37) - 75.4069*X(WET,GAR38)

- 22.6849*X(WET,GAR39) - 32.8004*X(WET,GAR40) - 29.9313*X(WET,GAR41)

- 30.0566*X(WET,GAR42) - 80.2254*X(WET,GAR43) - 61.6344*X(WET,GAR44)

- 59.9713*X(WET,GAR45) - 78.4565*X(WET,GAR46) - 135.7537*X(WET,GAR47)

- 68.5063*X(WET,GAR48) - 79.4347*X(WET,GAR51) - 32.6414*X(WET,OTH1)

- 23.5313*X(WET,OTH2) - 15.6978*X(WET,OTH3) - 44.4096*X(WET,OTH4)

- 5.9257*X(WET,OTH5) - 4.3939*X(WET,OTH6) - 12.1328*X(WET,OTH7)

- 4.9468*X(WET,OTH8) - 31.7288*X(WET,OTH9) - 64.9767*X(WET,OTH11)

- 2.2484*X(WET,OTH14) - 13.3191*X(WET,OTH15) - 5.6258*X(WET,OTH17)

- 64.7509*X(WET,OTH18) - 21.7948*X(WET,OTH19) - 36.5255*X(WET,OTH21)

- 60.5634*X(EHA,GAR9) - 88.8747*X(EHA,GAR10) - 69.1337*X(EHA,GAR11)

- 106.1442*X(EHA,GAR13) - 44.1183*X(EHA,GAR14) - 100.397*X(EHA,GAR15)

- 86.442*X(EHA,GAR16) - 41.9495*X(EHA,GAR17) - 40.8318*X(EHA,GAR18)

- 30.939*X(EHA,GAR19) - 102.9947*X(EHA,GAR20) - 50.5768*X(EHA,GAR21)

- 12.9812*X(EHA,GAR22) - 12.0054*X(EHA,GAR23) - 14.1026*X(EHA,GAR24)

- 53.0299*X(EHA,GAR25) - 68.0651*X(EHA,GAR26) - 91.9623*X(EHA,GAR27)

- 70.5254*X(EHA,GAR28) - 38.3363*X(EHA,GAR29) - 44.1295*X(EHA,GAR30)

- 61.5115*X(EHA,GAR31) - 47.018*X(EHA,GAR41) - 68.5847*X(EHA,GAR42)

- 145.843*X(EHA,GAR43) - 70.153*X(EHA,GAR44) - 20.051*X(EHA,GAR45)

- 76.1656*X(EHA,GAR46) - 103.0132*X(EHA,GAR47) - 180.5197*X(EHA,GAR55)

- 24.3612*X(EHA,OTH1) - 35.8285*X(EHA,OTH2) - 5.7231*X(EHA,OTH3)

- 16.026*X(EHA,OTH4) - 36.4989*X(EHA,OTH5) - 22.3146*X(EHA,OTH6)

- 45.8433*X(EHA,OTH7) - 166.096*X(EHA,OTH9) - 42.572*X(EHA,OTH11)

- 42.7655*X(EHA,OTH14) - 56.0027*X(EHA,OTH15) - 22.0721*X(EHA,OTH16)

- 23.1908*X(EHA,OTH17) - 34.3407*X(EHA,OTH19) - 24.6822*X(EHA,OTH20)

- 68.0106*X(WWL,GAR26) - 44.2351*X(WWL,GAR27) - 53.1489*X(WWL,GAR28)

- 80.7311*X(WWL,GAR29) - 78.521*X(WWL,GAR30) - 50.8191*X(WWL,GAR31)

- 28.4402*X(WWL,GAR32) - 43.3102*X(WWL,GAR33) - 66.7027*X(WWL,GAR34)

- 45.7475*X(WWL,GAR35) - 40.9094*X(WWL,GAR36) - 6.454*X(WWL,GAR37)

- 10.3401*X(WWL,GAR39) - 31.0561*X(WWL,GAR40) - 75.4113*X(WWL,GAR41)

- 46.7505*X(WWL,GAR42) - 99.4558*X(WWL,GAR43) - 95.5275*X(WWL,GAR44)

- 74.8363*X(WWL,GAR46) - 53.6297*X(WWL,GAR48) - 64.7023*X(WWL,GAR49)

- 60.0166*X(WWL,GAR51) - 44.1864*X(WWL,GAR52) - 35.0135*X(WWL,GAR53)

- 74.9459*X(WWL,GAR54) - 169.2372*X(WWL,GAR55) - 33.7313*X(WWL,OTH5)

- 13.7115*X(WWL,OTH6) - 21.5953*X(WWL,OTH7) - 25.7321*X(WWL,OTH8)

- 103.6912*X(WWL,OTH9) - 49.505*X(WWL,OTH13) - 41.917*X(WWL,OTH14)

- 59.5*X(WWL,OTH15) - 20.4748*X(WWL,OTH16) - 24.6554*X(WWL,OTH17)

- 25.545*X(WWL,OTH18) - 55.8494*X(WWL,OTH19) - 26.822*X(WWL,OTH21)

- 75.318*X(HIG,GAR9) - 111.2051*X(HIG,GAR15) - 85.5354*X(HIG,GAR16)

- 41.5627*X(HIG,GAR17) - 73.5715*X(HIG,GAR18) - 81.1755*X(HIG,GAR19)

- 294.3375*X(HIG,GAR20) - 59.5384*X(HIG,GAR22) - 62.964*X(HIG,GAR23)

- 47.8382*X(HIG,GAR24) - 88.6298*X(HIG,GAR25) - 55.5253*X(HIG,GAR26)

- 59.6053*X(HIG,GAR27) - 40.9817*X(HIG,GAR28) - 30.2709*X(HIG,GAR29)

- 33.7452*X(HIG,GAR30) - 49.6123*X(HIG,GAR31) - 29.427*X(HIG,GAR32)

- 49.7486*X(HIG,GAR33) - 88.9417*X(HIG,GAR34) - 48.8765*X(HIG,GAR35)

- 88.3764*X(HIG,GAR36) - 23.0469*X(HIG,GAR39) - 60.5346*X(HIG,GAR40)

- 8.6916*X(HIG,GAR41) - 37.0523*X(HIG,GAR42) - 70.5414*X(HIG,GAR43)

- 14.1751*X(HIG,GAR44) - 42.9116*X(HIG,GAR45) - 55.9076*X(HIG,GAR46)

- 68.1392*X(HIG,GAR47) - 58.519*X(HIG,GAR48) - 80.0934*X(HIG,GAR49)

- 84.9542*X(HIG,GAR50) - 69.3123*X(HIG,GAR51) - 116.1975*X(HIG,GAR55)

- 38.8514*X(HIG,OTH1) - 35.839*X(HIG,OTH2) - 16.6493*X(HIG,OTH3)

- 47.1636*X(HIG,OTH4) - 19.9128*X(HIG,OTH5) - 13.5583*X(HIG,OTH6)

- 29.3785*X(HIG,OTH7) - 25.3027*X(HIG,OTH8) - 102.998*X(HIG,OTH9)

- 28.5291*X(HIG,OTH10) - 34.106*X(HIG,OTH11) - 35.5958*X(HIG,OTH12)

- 26.7227*X(HIG,OTH14) - 27.4646*X(HIG,OTH15) - 13.8697*X(HIG,OTH16)

- 11.126*X(HIG,OTH17) - 55.5039*X(HIG,OTH18) - 17.4126*X(HIG,OTH19)

- 30.4179*X(HIG,OTH20) - 31.6211*X(HIG,OTH21) - 70.8113*X(OSA,GAR17)

- 85.2912*X(OSA,GAR19) - 278.8321*X(OSA,GAR20) - 41.7924*X(OSA,GAR22)

- 59.3214*X(OSA,GAR23) - 62.1994*X(OSA,GAR24) - 136.3042*X(OSA,GAR25)

- 73.836*X(OSA,GAR28) - 63.1353*X(OSA,GAR29) - 66.5346*X(OSA,GAR30)

- 25.8943*X(OSA,GAR39) - 41.4652*X(OSA,GAR41) - 48.4527*X(OSA,GAR42)

- 83.5455*X(OSA,GAR43) - 33.0308*X(OSA,GAR44) - 30.7428*X(OSA,GAR45)

- 27.8033*X(OSA,GAR46) - 3.3096*X(OSA,GAR47) - 54.4435*X(OSA,GAR48)

- 64.6818*X(OSA,GAR49) - 53.5441*X(OSA,GAR50) - 45.958*X(OSA,GAR51)

- 65.0723*X(OSA,GAR52) - 209.5742*X(OSA,GAR55) - 21.64*X(OSA,OTH3)

- 61.2285*X(OSA,OTH4) - 39.1979*X(OSA,OTH5) - 23.6686*X(OSA,OTH6)

- 175.8683*X(OSA,OTH9) - 17.0949*X(OSA,OTH10) - 7.6463*X(OSA,OTH11)

- 22.201*X(OSA,OTH12) - 25.5137*X(OSA,OTH16) - 70.0194*X(OSA,OTH18)

- 36.0261*X(OSA,OTH19) - 13.351*X(OSA,OTH20) - 20.746*X(OSA,OTH21)

- 110.3362*X(PUTN,GAR36) - 22.0191*X(PUTN,GAR37) - 65.8846*X(PUTN,GAR38)

- 18.0811*X(PUTN,GAR39) - 71.2084*X(PUTN,GAR40) - 72.6041*X(PUTN,GAR42)

- 59.2146*X(PUTN,GAR48) - 56.8216*X(PUTN,GAR49) - 80.7463*X(PUTN,GAR50)

- 62.1797*X(PUTN,GAR51) - 27.2323*X(PUTN,GAR52) - 16.774*X(PUTN,GAR53)

- 31.0237*X(PUTN,OTH12) - 24.7345*X(PUTN,OTH13) - 55.1696*X(PUTN,OTH18)

- 27.637*X(PUTN,OTH21) - 89.3914*X(LIS,GAR27) - 70.8248*X(LIS,GAR28)

- 107.0942*X(LIS,GAR36) - 31.5333*X(LIS,GAR37) - 78.1674*X(LIS,GAR38)

- 12.7941*X(LIS,GAR39) - 61.4251*X(LIS,GAR40) - 74.9749*X(LIS,GAR41)

```
     - 44.497*X(LIS,GAR42) - 66.2692*X(LIS,GAR43) - 75.5019*X(LIS,GAR44)

     - 30.4937*X(LIS,GAR46) - 111.1611*X(LIS,GAR47) - 13.8198*X(LIS,GAR48)

     - 2.1768*X(LIS,GAR49) - 39.9603*X(LIS,GAR50) - 15.0932*X(LIS,GAR51)

     - 21.8212*X(LIS,GAR52) - 49.3971*X(LIS,GAR53) - 76.3369*X(LIS,GAR54)

     - 47.6496*X(LIS,OTH5) - 45.2973*X(LIS,OTH7) - 14.4745*X(LIS,OTH10)

     - 58.0097*X(LIS,OTH11) - 6.2652*X(LIS,OTH12) - 22.023*X(LIS,OTH13)

     - 41.0812*X(LIS,OTH18) - 53.7067*X(LIS,OTH19) - 21.7369*X(LIS,OTH20)

     - 6.7582*X(LIS,OTH21) - 191.6*Y(WIN) - 281.4*Y(BRO) - 236.5*Y(DAR)

     - 202.6*Y(WAT) - 208.8*Y(MIL) - 217.2*Y(EGR) - 220.5*Y(WET)

     - 285.5*Y(EHA) - 178.4*Y(WWL) - 228.6*Y(HIG) - 198.7*Y(OSA)

     - 184.2*Y(PUTN) - 268.8*Y(LIS) + Z =E= 0 ;

---- DEMAND      =E=  ALL OF GARAGE I DEMAND MUST BE MET

DEMAND(GAR1)..  X(WIN,GAR1) + X(WAT,GAR1) + X(EGR,GAR1) =E= 1 ;

DEMAND(GAR2)..  X(WIN,GAR2) + X(WAT,GAR2) + X(EGR,GAR2) + X(WET,GAR2) =E= 1 ;

DEMAND(GAR3)..  X(WIN,GAR3) + X(BRO,GAR3) + X(WAT,GAR3) + X(EGR,GAR3)

     + X(WET,GAR3) =E= 1 ;

REMAINING 73 ENTRIES SKIPPED

---- SUPPLY      =L=  CAPACITY OF FACILITY F CANNOT BE EXCEEDED

SUPPLY(WIN)..  - 20.88*A(WIN) - 10.44*B(WIN) + 7.2*X(WIN,GAR1)

     + 6.44*X(WIN,GAR2) + 21.24*X(WIN,GAR3) + 27.4*X(WIN,GAR4)

     + 10.85*X(WIN,GAR5) + 3.89*X(WIN,GAR6) + 13.05*X(WIN,GAR7)

     + 14.67*X(WIN,GAR8) + 14.86*X(WIN,GAR9) + 23.87*X(WIN,GAR15)

     + 18.1*X(WIN,GAR16) + 13.15*X(WIN,GAR17) + 16.45*X(WIN,GAR18)

     + 16.65*X(WIN,GAR26) + 18.61*X(WIN,GAR27) + 15.35*X(WIN,GAR28)

     + 15.11*X(WIN,GAR29) + 14.84*X(WIN,GAR30) + 11.33*X(WIN,GAR31)

     + 5.08*X(WIN,GAR32) + 8.73*X(WIN,GAR33) + 20.13*X(WIN,GAR34)

     + 13.53*X(WIN,GAR35) + 18.83*X(WIN,GAR36) + 14.52*X(WIN,GAR40)

     + 38.55*X(WIN,GAR55) + 5.47*X(WIN,OTH1) + 7.15*X(WIN,OTH2)

     + 6.83*X(WIN,OTH5) + 3.96*X(WIN,OTH6) + 6.54*X(WIN,OTH8)

     + 25.39*X(WIN,OTH9) + 8.96*X(WIN,OTH14) + 13.13*X(WIN,OTH15)

     + 2.36*X(WIN,OTH16) + 4.95*X(WIN,OTH17) - 120.48*Y(WIN) =L= 0 ;
```

```
SUPPLY(BRO)..  - 20.88*A(BRO) - 10.44*B(BRO) + 21.24*X(BRO,GAR3)

      + 10.85*X(BRO,GAR5) + 3.89*X(BRO,GAR6) + 13.05*X(BRO,GAR7)

      + 14.67*X(BRO,GAR8) + 14.86*X(BRO,GAR9) + 16.16*X(BRO,GAR10)

      + 12.73*X(BRO,GAR11) + 20.27*X(BRO,GAR12) + 22.45*X(BRO,GAR13)

      + 11.99*X(BRO,GAR14) + 23.87*X(BRO,GAR15) + 18.1*X(BRO,GAR16)

      + 13.15*X(BRO,GAR17) + 16.45*X(BRO,GAR18) + 18.35*X(BRO,GAR19)

      + 45*X(BRO,GAR20) + 19.36*X(BRO,GAR21) + 13.04*X(BRO,GAR22)

      + 14.19*X(BRO,GAR23) + 13.47*X(BRO,GAR24) + 32.9*X(BRO,GAR25)

      + 5.47*X(BRO,OTH1) + 7.15*X(BRO,OTH2) + 2.95*X(BRO,OTH3)

      + 9.93*X(BRO,OTH4) - 89.16*Y(BRO) =L= 0 ;

SUPPLY(DAR)..  - 20.88*A(DAR) - 10.44*B(DAR) + 14.67*X(DAR,GAR8)

      + 16.16*X(DAR,GAR10) + 12.73*X(DAR,GAR11) + 20.27*X(DAR,GAR12)

      + 22.45*X(DAR,GAR13) + 11.99*X(DAR,GAR14) + 16.45*X(DAR,GAR18)

      + 18.35*X(DAR,GAR19) + 45*X(DAR,GAR20) + 19.36*X(DAR,GAR21)

      + 14.19*X(DAR,GAR23) + 2.95*X(DAR,OTH3) + 9.93*X(DAR,OTH4)

      - 141.36*Y(DAR) =L= 0 ;

REMAINING 10 ENTRIES SKIPPED

---- EXPAND1     =L=  FIRST EXPANSION NOT ALLOWED UNLESS FACILITY IS OPEN

EXPAND1(WIN)..  A(WIN) - Y(WIN) =L= 0 ;

EXPAND1(BRO)..  A(BRO) - Y(BRO) =L= 0 ;

EXPAND1(DAR)..  A(DAR) - Y(DAR) =L= 0 ;

REMAINING 10 ENTRIES SKIPPED

---- EXPAND2     =L=  ADDITIONAL EXPANSIONS NOT ALLOWED WITHOUT FIRST

EXPAND2(WIN)..  - 8*A(WIN) + B(WIN) =L= 0 ;

EXPAND2(BRO)..  - 8*A(BRO) + B(BRO) =L= 0 ;

EXPAND2(DAR)..  - 8*A(DAR) + B(DAR) =L= 0 ;

REMAINING 10 ENTRIES SKIPPED

---- TIGHTEN     =L=  EXTRA CONSTRAINTS ADDED TO TIGHTEN L.P. BOUNDS

TIGHTEN(WIN,GAR1)..  X(WIN,GAR1) - Y(WIN) =L= 0 ;

TIGHTEN(WIN,GAR2)..  X(WIN,GAR2) - Y(WIN) =L= 0 ;
```

```
TIGHTEN(WIN,GAR3)..  X(WIN,GAR3) - Y(WIN) =L= 0 ;

REMAINING 143 ENTRIES SKIPPED


---- TOTFAC      =L=  CONSTRAINT ON TOTAL NUMBER OF FACILITIES

TOTFAC..  Y(WIN) + Y(BRO) + Y(DAR) + Y(WAT) + Y(MIL) + Y(EGR) + Y(WET) + Y(EHA)

     + Y(WWL) + Y(HIG) + Y(OSA) + Y(PUTN) + Y(LIS) =L= 13 ;


---- A           BINARY VARIABLE INDICATING IF TWO BAYS ARE ADDED

A(WIN)
                (.LO, .L, .UP = 0, 0, 1)
      -22.15    COST
      -20.88    SUPPLY(WIN)
        1       EXPAND1(WIN)
       -8       EXPAND2(WIN)

A(BRO)
                (.LO, .L, .UP = 0, 0, 1)
      -22.15    COST
      -20.88    SUPPLY(BRO)
        1       EXPAND1(BRO)
       -8       EXPAND2(BRO)

A(DAR)
                (.LO, .L, .UP = 0, 0, 1)
      -22.15    COST
      -20.88    SUPPLY(DAR)
        1       EXPAND1(DAR)
       -8       EXPAND2(DAR)

REMAINING 10 ENTRIES SKIPPED


---- B           NUMBER OF BAYS ADDED ABOVE TWO

B(WIN)
                (.LO, .L, .UP = 0, 0,  +INF)
       -8.075   COST
      -10.44    SUPPLY(WIN)
        1       EXPAND2(WIN)

B(BRO)
                (.LO, .L, .UP = 0, 0,  +INF)
       -8.075   COST
      -10.44    SUPPLY(BRO)
        1       EXPAND2(BRO)

B(DAR)
                (.LO, .L, .UP = 0, 0,  +INF)
       -8.075   COST
      -10.44    SUPPLY(DAR)
        1       EXPAND2(DAR)

REMAINING 10 ENTRIES SKIPPED
```

```
---- X          SHIPMENT PERCENTAGES

X(WIN,GAR1)
                (.LO, .L, .UP = 0, 0,  +INF)
     -16.7617   COST
       1        DEMAND(GAR1)
       7.2      SUPPLY(WIN)
       1        TIGHTEN(WIN,GAR1)

X(WIN,GAR2)
                (.LO, .L, .UP = 0, 0,  +INF)
      -7.7888   COST
       1        DEMAND(GAR2)
       6.44     SUPPLY(WIN)
       1        TIGHTEN(WIN,GAR2)

X(WIN,GAR3)
                (.LO, .L, .UP = 0, 0,  +INF)
     -13.63     COST
       1        DEMAND(GAR3)
      21.24     SUPPLY(WIN)
       1        TIGHTEN(WIN,GAR3)

REMAINING 477 ENTRIES SKIPPED


---- Y          BINARY VARIABLE INDICATING IF FACILITY IS KEPT OPEN


Y(WIN)
                (.LO, .L, .UP = 0, 0, 1)
    -191.6      COST
    -120.48     SUPPLY(WIN)
      -1        EXPAND1(WIN)
      -1        TIGHTEN(WIN,GAR1)
      -1        TIGHTEN(WIN,GAR2)
      -1        TIGHTEN(WIN,GAR3)
      -1        TIGHTEN(WIN,GAR4)
      -1        TIGHTEN(WIN,GAR5)
      -1        TIGHTEN(WIN,GAR7)
      -1        TIGHTEN(WIN,GAR16)
      -1        TIGHTEN(WIN,GAR31)
      -1        TIGHTEN(WIN,GAR32)
      -1        TIGHTEN(WIN,GAR33)
       1        TOTFAC

Y(BRO)
                (.LO, .L, .UP = 0, 0, 1)
    -281.4      COST
     -89.16     SUPPLY(BRO)
      -1        EXPAND1(BRO)
      -1        TIGHTEN(BRO,GAR8)
      -1        TIGHTEN(BRO,GAR9)
      -1        TIGHTEN(BRO,GAR10)
      -1        TIGHTEN(BRO,OTH1)
       1        TOTFAC

Y(DAR)
                (.LO, .L, .UP = 0, 0, 1)
    -236.5      COST
    -141.36     SUPPLY(DAR)
      -1        EXPAND1(DAR)
      -1        TIGHTEN(DAR,GAR11)
      -1        TIGHTEN(DAR,GAR12)
      -1        TIGHTEN(DAR,GAR13)
```

```
      -1        TIGHTEN(DAR,GAR14)
       1        TOTFAC

REMAINING 10 ENTRIES SKIPPED


---- Z          TOTAL COST


Z
                (.LO, .L, .UP =  -INF, 0,  +INF)
       1        COST


MODEL STATISTICS

BLOCKS OF EQUATIONS      7     SINGLE EQUATIONS     263
BLOCKS OF VARIABLES      5     SINGLE VARIABLES     520
NON ZERO ELEMENTS     1867     DISCRETE VARIABLES    26


               S O L V E     S U M M A R Y

     MODEL   CONNDOT             OBJECTIVE  Z
     TYPE    MIP                 DIRECTION  MINIMIZE
     SOLVER  ZOOM                FROM LINE  597

**** SOLVER STATUS     1 NORMAL COMPLETION
**** MODEL STATUS      1 OPTIMAL
**** OBJECTIVE VALUE             3441.0644

 RESOURCE USAGE, LIMIT         663.000  1000000.000
 ITERATION COUNT, LIMIT       3250       200000

 Z O O M / X M P    ---    Version 2.1 Oct 1988

 Courtesy of Dr Roy E. Marsten,
             Department of Management Information Systems,
             University of Arizona,
             Tucson     Arizona  85721,  U.S.A.

 Work space needed (estimate)   --   35283 words.
 Work space available           --   35283 words.

 The branch and bound tree contained     62 nodes (max.  1500 nodes).

 Iterations: Initial LP             651, Time:  105.000
             Heuristic              519,         74.0000
             Branch and bound      1680,        424.000
             Final LP               400,         50.0000


----     VARIABLE  X.L            SHIPMENT PERCENTAGES

            GAR1        GAR2        GAR3        GAR4        GAR5        GAR6

WIN        1.000       1.000       1.000       1.000       1.000       1.000

   +        GAR7        GAR8        GAR9       GAR10       GAR11       GAR12

WIN        1.000       0.359
WAT                    0.641       1.000       1.000
MIL                                                        1.000       1.000
```

+	GAR13	GAR14	GAR15	GAR16	GAR17	GAR18
WAT			1.000	1.000	1.000	1.000
MIL	1.000	1.000				

+	GAR19	GAR20	GAR21	GAR22	GAR23	GAR24
MIL	1.000	1.000	1.000		1.000	1.000
OSA				1.000		

+	GAR25	GAR26	GAR27	GAR28	GAR29	GAR30
MIL	0.290					
WET	0.710	1.000	1.000	1.000	1.000	1.000

+	GAR31	GAR32	GAR33	GAR34	GAR35	GAR36
WIN	1.000	1.000	1.000			
WET				1.000	1.000	
WWL						1.000

+	GAR37	GAR38	GAR39	GAR40	GAR41	GAR42
WET						1.000
WWL	1.000	1.000	1.000	1.000		
OSA					1.000	

+	GAR43	GAR44	GAR45	GAR46	GAR47	GAR48
OSA	0.163	1.000	1.000	1.000	1.000	
LIS	0.837					1.000

+	GAR49	GAR50	GAR51	GAR52	GAR53	GAR54
WWL					1.000	0.488
LIS	1.000	1.000	1.000	1.000		0.512

+	GAR55	OTH1	OTH2	OTH3	OTH4	OTH5
WAT		1.000	1.000			
MIL				1.000	1.000	
WET	1.000					1.000

+	OTH6	OTH7	OTH8	OTH9	OTH10	OTH11
WET	1.000	1.000	1.000	1.000		
OSA					1.000	1.000

+	OTH12	OTH13	OTH14	OTH15	OTH16	OTH17
WET			1.000	1.000	1.000	1.000
LIS	1.000	1.000				

+	OTH18	OTH19	OTH20	OTH21
WET		1.000		
WWL	1.000			
OSA			1.000	
LIS				1.000

```
----    VARIABLE  Y.L           BINARY VARIABLE INDICATING IF FACILITY IS
                                    KEPT OPEN

WIN 1.000,    WAT 1.000,    MIL 1.000,    WET 1.000,    WWL 1.000,    OSA 1.000
LIS 1.000

----    VARIABLE  A.L           BINARY VARIABLE INDICATING IF TWO BAYS ARE
                                    ADDED

WAT 1.000,    MIL 1.000,    WET 1.000

----    599 VARIABLE  B.L           NUMBER OF BAYS ADDED ABOVE TWO

WAT 2.396,    MIL 3.640,    WET 8.000
```

APPENDIX E. SURVEY DESCRIPTION AND RESULTS

This appendix describes the results of a survey conducted in the summer of 1991. The survey instrument, shown with the transmittal letter in Figures E.1 and E.2 consisted of a two-page questionnaire. It was mailed to each of the fifty states and to the Canadian provinces. Thirty three states and seven provinces responded. The results are given in Table E.1.

Many varieties of responsibilities and methods of handling equipment maintenance are represented. In order to make comparisons to CONNDOT operations, it is necessary to select states having systems somewhat similar to CONNDOT in terms of equipment repair logistics. For present purposes, it is most important that this selection be based on whether the equipment is repaired where it is stored or at a separate repair facility. Thus, if we restrict our analysis to states having at least fifty percent of their equipment served at separate facilities, we are left with 18 states to which comparisons can be made.

Figures E.3 through E.10 graphically demonstrate the comparative statistics.

The most obvious statistic is garage density, i.e., garages per mile of roadway maintained. Plotted in Figure E.3 is garages per <u>centerline-mile</u>. As can be seen, Connecticut is well above both the mean and the median in terms of garages per 1000 centerline-miles.

Recognizing that a better statistic might be garages per <u>lane-mile</u>, the questionnaire asked for both centerline-miles and lane-miles. Unfortunately, since some of the respondents appeared to be confused as to the meaning of the term "lane-miles", the data based on this statistic is less reliable than that based on centerline-miles. For this reason, Figure E.4 should be viewed with caution. Nevertheless, the conclusion based on lane-miles is the same as that based on centerline-miles, i.e. Connecticut is above both the mean and the median.

In an attempt to account for the compactness of the State, a statistic, here termed "area density", A_d, was calculated from

$$A_d = (G/mA) \times 10^6$$

where
G = number of garages
m = number of centerline-miles
A = area of the state (sq.mi.)

This is the statistic plotted in Figure E.5. Note that A_d for Connecticut is more than five times the mean of the 19 states and nearly eighteen times the median. In fact, Connecticut, of the nineteen states shown, has the highest density of garages by this measure.

If it is true that Connecticut has a relatively high number of garages for the size of the roadway network maintained, it would seem that the amount of equipment served by each garage should be lower than the average. Such is not the case, however. As seen in Figure E.6, the number of pieces of equipment (in categories 1 through 3) per equipment garage for Connecticut is considerably higher than the mean and much higher than the median. As an aside, we might note from Figure E.7 that the number of pieces of equipment per road garage for Connecticut is extremely high compared to the rest of the states. Only Illinois is higher.

One possible explanation for the somewhat contradictory findings above is that Connecticut maintains a larger equipment fleet than the other states. When only raw numbers are considered, as shown in Figure E.8, Connecticut is very close to average. However, when the network size is taken into account, the size of the Connecticut fleet is well above the average. This is shown in Figures E.9 and E.10. Figure E.9 is based on total equipment in categories 1 through 3, while Figure E.10 is based on equipment serviced at a maintenance garage.

There is a wealth of additional information available from the survey, but for present purposes the comparative statistics presented above will suffice. Based on these, it appears that, for the size of the State, CONNDOT maintains a relatively high number of pieces of equipment and services that equipment in a relatively high number of garages.

EQUIPMENT MAINTENANCE SURVEY

JHRP 90-6 AUGUST 1991

NAME OF AGENCY: ____________
NAME OF PERSON COMPLETING FORM: ____________
TITLE: ____________
MAILING ADDRESS: ____________

TELEPHONE NUMBER: ____________

1. PLEASE GIVE US YOUR BEST ESTIMATES FOR THE FOLLOWING STATISTICS:

a. Centerline-miles of roadway maintained: ______
b. Lane-miles of roadway maintained: ______
c. Number of roadway maintenance garages: ______
d. Number of equipment maintenance garages: ______
e. Number of equipment maintenance garages with stockrooms: ______
f. Number of mechanics and welders: ______
g. Number of supervisors: ______
h. Number of clerks: ______

i. Equipment workload and downtime by category:

CATE-GORY	DESCRIPTION	NUMBER	% OF TOTAL WORKLOAD*	AVERAGE DOWNTIME**
1	Heavy Truck	____	____	____
2	Light Truck	____	____	____
3	Heavy Motorized (e.g. compressors)	____	____	____
4	Small Motorized (e.g. chainsaws)	____	____	____
5	Other requiring little maint.	____	____	____
6	Automobiles	____	____	____

Notes: * Numbers in this column should sum to 100.
** "Downtime" is the number of days the equipment is not available given as a percentage of the total working days in the period.

2. PLEASE CHECK THE BOX THAT BEST DESCRIBES YOUR SYSTEM.

____ Equipment is maintained where it is housed.
____ Equipment visits a separate facility for maintenance.
____ Combination of the above (please estimate the percentage of each, based on repair hours)

3. DO ALL EQUIPMENT MAINTENANCE FACILITIES PERFORM ESSENTIALLY ALL TYPES OF REPAIRS, OR ARE SOME FACILITIES SPECIALIZED? NO ___ YES ___ .
IF SOME ARE SPECIALIZED, PLEASE EXPLAIN.

EQUIPMENT MAINTENANCE SURVEY - PAGE 2

4. DOES YOUR AGENCY USE ANY PRODUCTIVITY STANDARDS? NO ____ YES ____
IF YES, PLEASE EXPLAIN.

5. APPROXIMATELY WHAT PERCENTAGE OF ROADWAY MAINTENANCE ACTIVITIES ARE CONTRACTED OUT? ________

6. APPROXIMATELY WHAT PERCENTAGE OF EQUIPMENT MAINTENANCE ACTIVITIES ARE CONTRACTED OUT? ________

7. PLEASE GIVE US ANY OTHER INFORMATION YOU THINK MIGHT BE HELPFUL FOR OUR STUDY.

8. WOULD YOU LIKE TO RECEIVE A COPY OF THE SURVEY RESULTS? YES ___ NO ___

THANK YOU FOR YOUR ASSISTANCE

Figure E.1 The Questionnaire

August 6, 1991

Dear________________:

We are conducting a study for the Connecticut Department of Transportation (ConnDOT) dealing with equipment maintenance facilities. For your information, we have enclosed a map showing the locations of the thirteen (13) equipment maintenance facilities (squares) and fifty-five (55) roadway maintenance facilities (circles) operated by ConnDOT. Assignment of equipment for servicing is indicated by the lines connecting circles and squares. In the ConnDOT system, each piece of equipment is housed at a roadway maintenance facility and serviced at an equipment maintenance facility. All equipment housed at a given roadway maintenance facility goes to the same equipment maintenance facility for repair. All equipment maintenance facilities perform essentially all types of maintenance.

We are studying the potential economies that might be gained by consolidation of certain of the equipment maintenance facilities. As part of our effort, we are surveying other highway agencies such as yours. While we recognize that each agency operates under many unique conditions, we feel that an inter-agency comparison of certain statistics could be helpful. To that end, we are requesting your assistance in providing several statistics related to your operation. The enclosed survey form should be relatively easy to complete. If you have questions on any item, simply answer to the best of your ability or leave it blank. Since we will be preparing the final report beginning in September, we would appreciate receiving your reply as soon as possible. If you would like a copy of the final survey results, please so indicate on the survey form.

Thank you for your cooperation.

Very truly yours,

Christian F. Davis, Ph.D., P.E.
Professor

Enclosures (2)

Figure E.2 Questionnaire cover letter.

			AL	AK	AR	DE	FL	ID	IL	IA	LA	MA	ME	MI
1	a Centerline-miles of roadway		11000	5600	16203	4750	11801	5000	17176	10458	17286	2862	7499	6159
1	b Lane-miles of roadway		27000	13000	34779	12500	36775	11622	0	24983	39102	12668	15602	7531
1	c Number road garages		0	85	84	15	51	40	104	138	62	122	100	33
1	d Number equipment garages		42	47	95	14	30	6	14	114	4	9	43	36
1	e Number w/ stockrooms		9	8	11	3	30	6	14	114	10	9	43	36
1	f Number mechanics and welders		156	143	108	78	135	42	0	154	169	60	125	96
1	g Number supervisors		9	6	136	6	33	12	0	148	34	15	33	15
1	h Number clerks		25	26	32	4	30	18	0	0	30	6	28	16
1	i Equipment workload													
	Number in category:													
		1	614	405	1086	362	1227	181	2050	1215	1259	80	562	450
		2	1543	1500	1138	178	1514	340	1425	1239	1351	771	298	1500
		3	607	700	1489	200	1615	640	1600	866	136	33		800
		4	1000	0	1024	500		300	1000	798	55	62		700
		5	500	2100	2125	200	1555	1500	0	6852		400		1200
		6	237	2000	312	220	2146	105	700	593	464	364	130	450
	% workload in category:													
		1	15	20		20		15		19		15	72	30
		2	30	15		10		15		10		35	21	25
		3	20	35		30		25		12		10		10
		4	20	0		20		10		7		5		5
		5	10	10		10		30		48		5		5
		6	5	20		10		5		4		30	7	25
	Ave. downtime in cat.:													
		1	0					10				15	26	20
		2	0					10				4	34	15
		3	0					10				8		15
		4	0					10				2		10
		5	0					10				3		10
		6	0					10				2	40	10
2	Percent maintained where house		90	80		40	90	10	0	100	100	25	40	70
2	Percent maintained separate:		10	20		60	10	90	0	0	0	75	60	30
3	All perform same? (1=yes):		0	0	1	1	1	1	1	1	1	1	0	1
4	Productivity standards? (1=yes		1	0	0	0	1	0		0	0	1	1	0
5	Percent road contracted:		10	10	2	0.5	18	10		15	2	60	0	75
6	Percent equipment contracted:		20	10	1	0	20	10		10	3	30	5	25

Table E.1 Survey results.

		MN	MO	MT	NE	NV	NJ	NY	ND	OK	OR	PA	SC
1	a Centerline-miles of roadway	12100	32250	8129	10000		2356	16000	8320	12256	8474	41000	41289
1	b Lane-miles of roadway	28900	74285	19464	23000	12875	10472	42000	16640	28527	24285	78000	87500
1	c Number road garages	135	356	130	109	48	75	292	72	100	88	480	47
1	d Number equipment garages	18	10	15	71	10	12	10	8	108	3	70	0
1	e Number w/ stockrooms	16	10	12	71	7	12	65	8	100	3	70	1
1	f Number mechanics and welders	150	260	68	124	139	135	378	40	121	110	640	291
1	g Number supervisors	22	10	12	105	17	44	60	16	156	24	70	47
1	h Number clerks		45	11	31	5	26	37	8	156	20	61	57
1	i Equipment workload												
	Number in category:												
	1	1022	1735	81	650	130	700	1260	50	650	690	3000	150
	2	1352	730	412	410	130	880	2345	320	650	904	4400	1050
	3	96	2500		430	123	500	4150	150	1245	100	2200	3500
	4	497	500		220		2500	2818	70	1073	50	2000	2000
	5		400		1000	35	1500	100		2000	1110		
	6	360	635	73	320	100	649	484	1700	240	1300	725	1340
	% workload in category:												
	1	30	35	25	80	36	30	35			30	50	5
	2	25	10	75	15	37	30	8			30	10	15
	3	20	30		0	12	10	47			15	30	50
	4	15	10		0		5	8			5	10	5
	5		5		0	5	5	2			15		
	6	10	10		5	10	20				5		25
	Ave. downtime in cat.:												
	1			3		19	6	8				5	5
	2			5		16	6	8				5	5
	3					2	12	8				5	7
	4						9	8				5	15
	5					9	6	8					
	6			3		4		3					3
2	Percent maintained where house	70	100	0	80	60	0	100	20	50	10	30	100
2	Percent maintained separate:	30	0	0	20	40	100	100	80	50	90	70	0
3	All perform same? (1=yes):	1	0	1	1	0	0	1	1	1	1	1	1
4	Productivity standards? (1=yes	0	0	1	0	1	1	1	0	0	1	0	0
5	Percent road contracted:	10	5	10	5	10	50	30	35	25	5	30	20
6	Percent equipment contracted:		0	5	5	2	1	10	40	20	50	5	5

Table E.1 Survey results (continued).

	SD	TN	TX	VT	VA	WA	WV	WI	WY	ALBERTA(AB)	N.W. Terr (NT
1 a Centerline-miles of roadway	7890	13460	72000	3064	43500	6998	34036	12000	6771	21055	1554
1 b Lane-miles of roadway	18430	32116	183000	7688		17504	51348	28800	7684	47510	3100
1 c Number road garages	67	121	345	58	230	97	121		54	90	9
1 d Number equipment garages	6	30	26	58	70	37	95		24	30	8
1 e Number w/ stockrooms	6	30	26	16	70	6	12		0	30	8
1 f Number mechanics and welders		140	382	42	389	150	429		72	220	15
1 g Number supervisors		30	53	9	105	20	124		25	33	2
1 h Number clerks		16	62	9	76	25	95		0	16	1
1 i Equipment workload											
Number in category:											
1	590	821	493	135	2263	500	1192		400	560	30
2	396	1426	8287	100	2564	1150	1579		540	1345	43
3	669	1377	3553	75	1436	600	1059		350	455	100
4	624	400		60	5500	150	1117			0	50
5	1718	247	1059	50		1000	311			1617	15
6	130	624	1136	45	2800	650	409		100	0	8
% workload in category:											
1	30	25		29		30	30			25	35
2	30	20		21		15	30			40	25
3	15	30		16		25	8			20	15
4	5	3		13		10	1				5
5	10	2		11		5	1			10	10
6	10	20		10		15	30				10
Ave. downtime in cat.:											
1	4	5	5	5		3	4			13	15
2	1.5	3	3	2		1	3			8	6
3	6	8	4	1		5	5			17	5
4	1	1		1		1	3				5
5		5	1	1		0.5	5				3
6	0.5	2	2	2		1	3				3
2 Percent maintained where house	50	25	90	100	15	20				20	75
2 Percent maintained separate:	50	75	10	0	85	80				80	25
3 All perform same? (1=yes):	1	0	1	1	1	1	0		1	0	1
4 Productivity standards? (1=yes	0	0	0	0	1	0	1		1	1	1
5 Percent road contracted:	32	30	30	4	25	15	8		30	20	50
6 Percent equipment contracted:	0	15	25	0	5	10	5	100	2	25	50

Table E.1 Survey results (continued)

			NEWFND(NF	NEWBRN(NB	NOVA(NS)	ONTARIO(OT	QUEBEC(QB
1	a Centerline-miles of roadway		5250		16194	13463	14904
1	b Lane-miles of roadway		10500	30000		33770	22977
1	c Number road garages		68	120	85	239	152
1	d Number equipment garages		45	35	12	18	61
1	e Number w/ stockrooms		29	22	12	18	61
1	f Number mechanics and welders		176	196	154	213	318
1	g Number supervisors		89	40	22	58	56
1	h Number clerks		64		32	21	97
1	i Equipment workload						
	Number in category:						
		1	312	1670	387	1169	635
		2	291	800	140	1250	1204
		3	384	200	374	778	1196
		4	353			12766	1387
		5	1496	300	512		
		6	88	300		627	129
	% workload in category:						
		1	11		30	14.5	25
		2	10		15	65	35
		3	13		30	1	15
		4	12			1.5	10
		5	51		25		
		6	3			18	15
	Ave. downtime in cat.:						
		1	26		20	9	35
		2	9		10	9	12
		3	25		25	6	50
		4	2			1.5	50
		5	4		5		
		6	7			4	12
2	Percent maintained where house		100		0	80	70
2	Percent maintained separate:		0		100	20	30
3	All perform same? (1=yes):		1	1	1	1	1
4	Productivity standards? (1=yes		0	0	0	1	0
5	Percent road contracted:		5	0	25	22	45
6	Percent equipment contracted:		10	30	5	30	7

Table E.1 Survey results (continued).

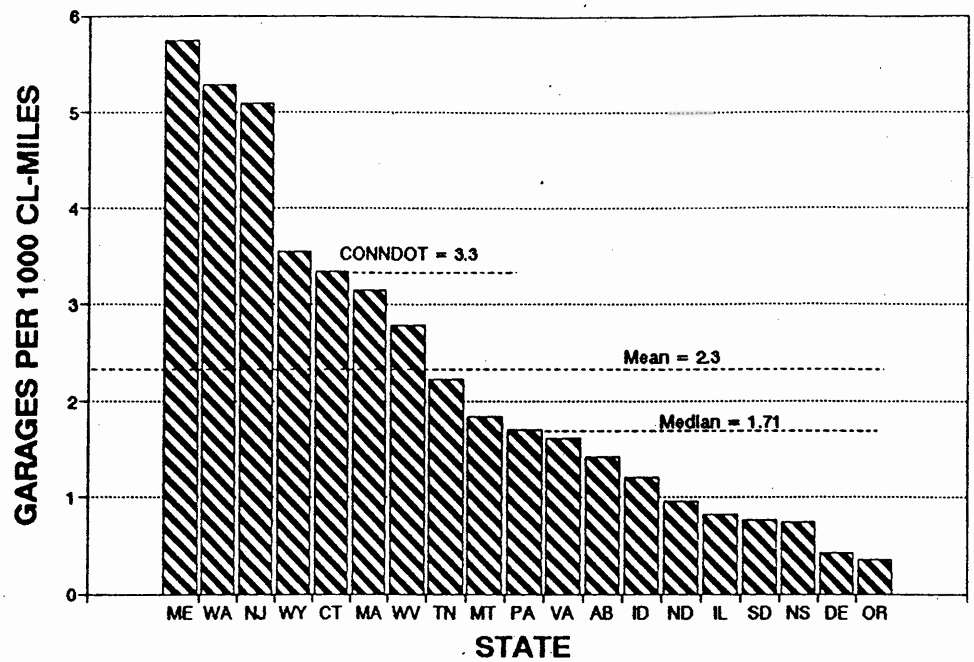


Figure E.3 Repair garages per 1000 centerline-miles, by state

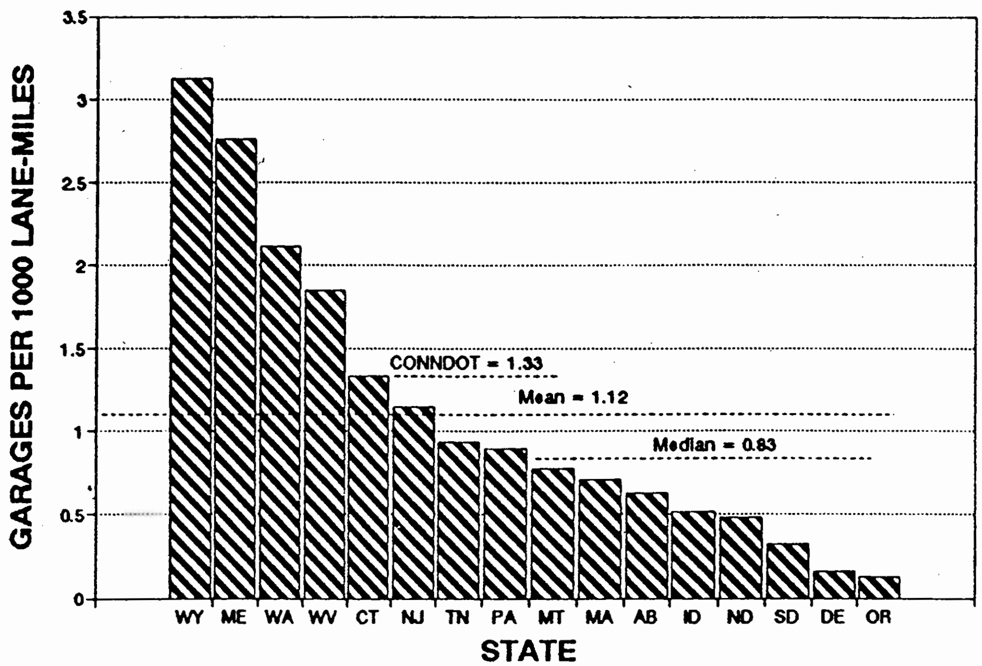


Figure E.4 Repair garages per 1000 lane-miles, by state

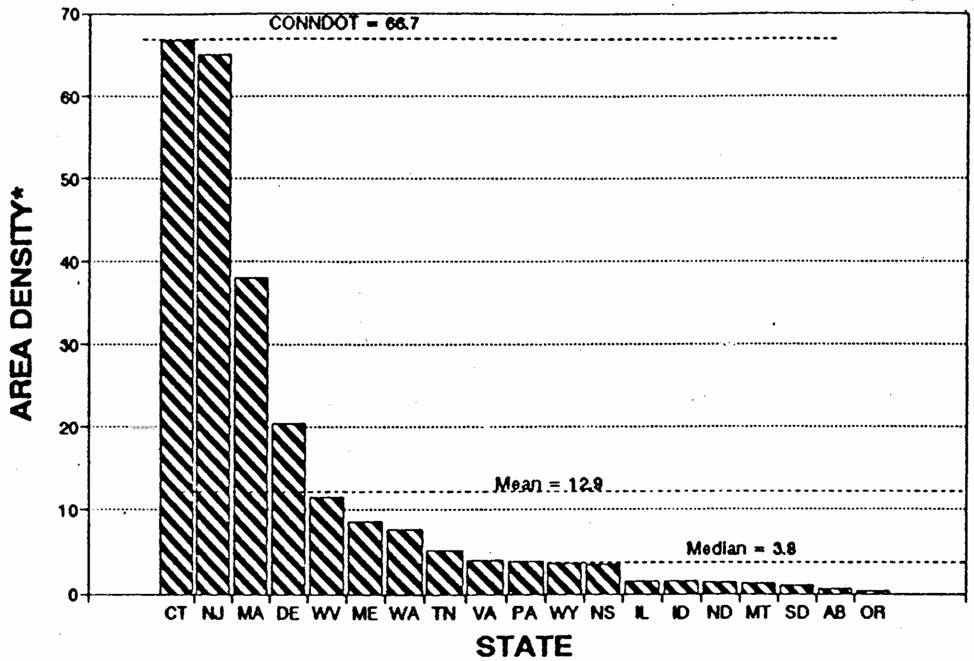


Figure E.5 Repair garage area density, by state

(* The area density measure considers number of garages, number of centerline-miles, and square miles of the State.)

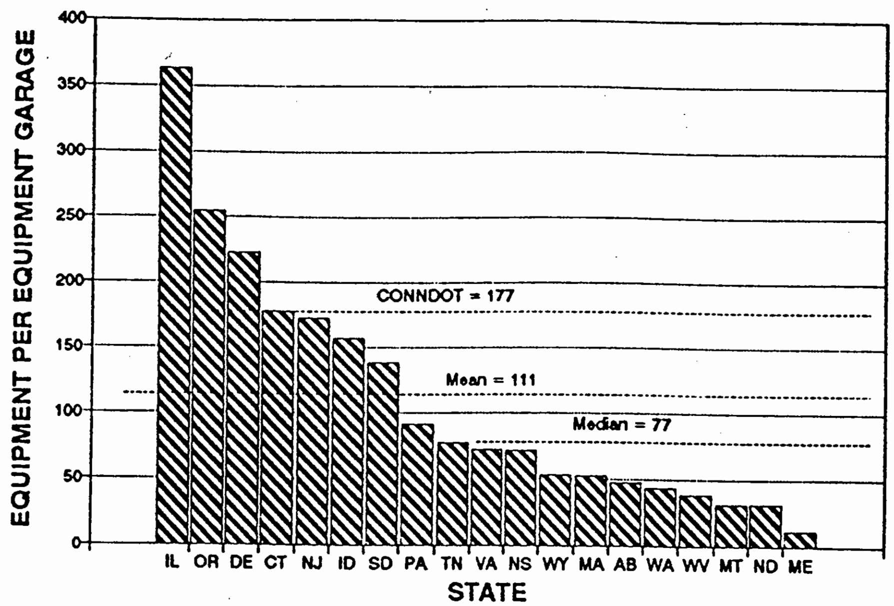


Figure E.6 Quantity of equipment per repair garage, by state

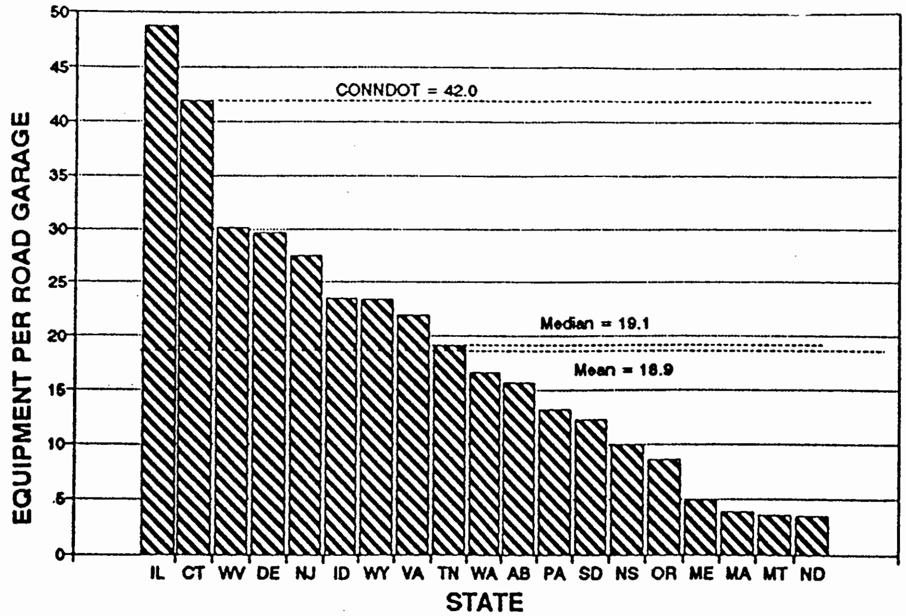


Figure E.7 Quantity of equipment per roadway garage, by state

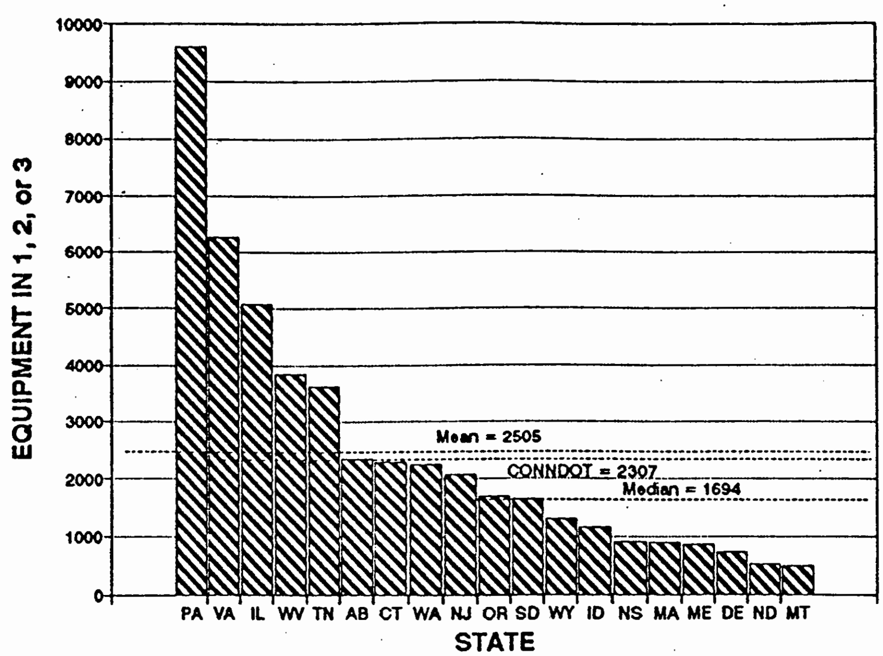


Figure E.8 Quantity of equipment in categories 1 through 3, by state

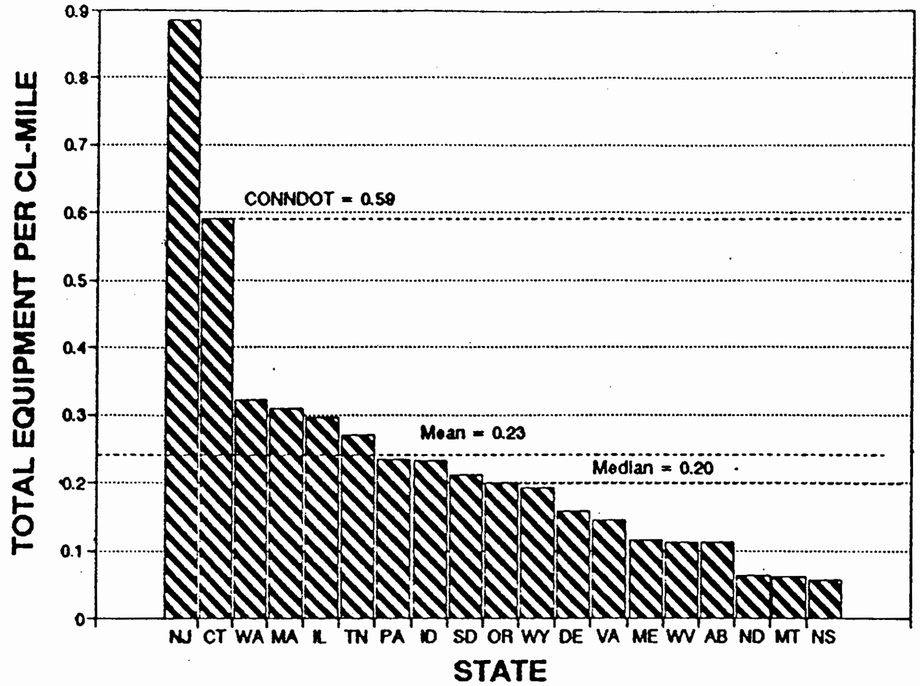


Figure E.9 Equipment per centerline-mile, by state

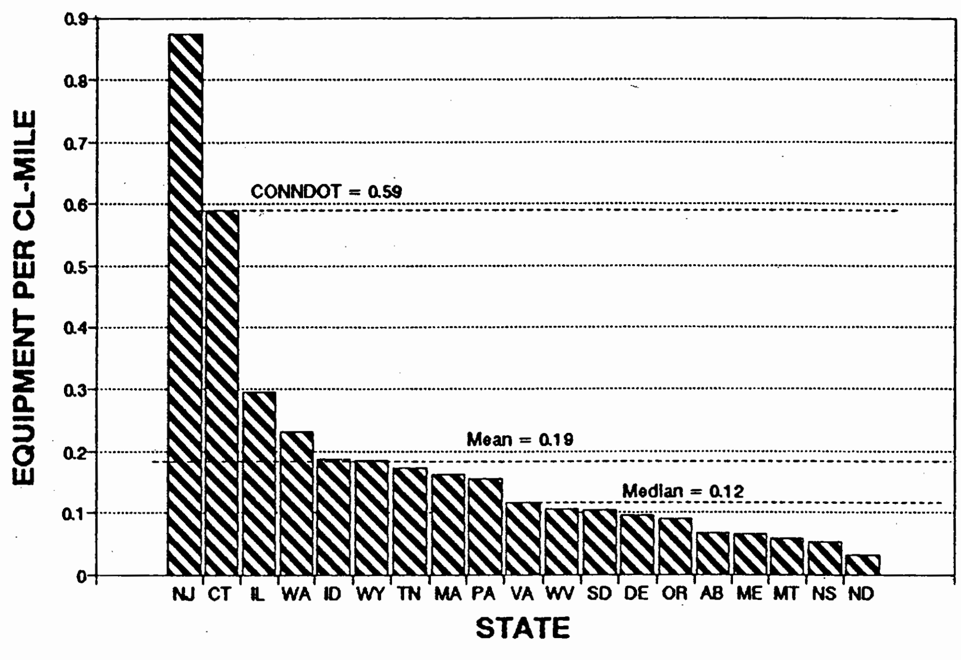


Figure E.10 Equipment maintained at repair garages per centerline-mile, by state. (Note: This excludes equipment maintained elsewhere.)

APPENDIX F. REASSIGNMENT OF MECHANICS

This appendix presents methods that could be used to help determine how mechanics should be reassigned if the repair system is reconfigured. Recommendations for reassignments are developed for both the ten facility and eleven facility options recommended in this report.

The basic concept underlying the analysis is that mechanics should be distributed amongst facilities in proportion to workloads. To estimate workloads, information from Table B.1 is used in a manner similar to the capacity analysis performed in Appendix B. Based on the average annual repair hours of the equipment, weights are established for each equipment category. These weights, which are equal to the category's average annual repair hours divided by that of Category 1A, are as follows:

$W'_{1A} = 1$, $W'_{1B} = .59$, $W'_2 = .33$, $W'_3 = .38$, $W'_4 = .04$, $W'_5 = .09$.

The only weights that are different than those used for the work bay capacity analysis performed in Appendix B are those of categories 4 and 5. These were both zero in the analysis done in Appendix B because equipment in those categories do not occupy full work bays. When considering the workload of mechanics, however, the requirements of these categories need to be considered.

Using these weights, the mechanics' workload offered by garage i, D'_i, can be calculated as follows:

$$D'_i = \sum_{e=1A}^{5} W'_e G_{ei}$$

Where G_{ei} is the quantity of type e equipment at garage i. Table F.1 presents D'_i values for each garage and other source of equipment in the repair system. Table B.2 in Appendix B gives information about the location and function of each garage and other equipment source.

By summing up all sources of requirements served by a facility in the current configuration, we obtain the total mechanics' workload for that facility. These values are presented in Table F.2, along with the actual number of mechanics at each facility, as of September, 1991. The actual numbers of mechanics shown in this table reflect weights of 1 for full mechanics, .75 for grade 3 mechanics, and .5 for grade 2 mechanics. These weights and the numbers of mechanics were established through consultations with Mr. James E. Lewis, Jr., Equipment Repair Supervisor.

Table F.1 Weighted average mechanics' workloads (D_i') offered by garages and other sources of requirements.

GAR1	8.63	GAR2	7.81	GAR3	29.79
GAR4	32.68	GAR5	14.12	GAR6	5.20
GAR7	16.47	GAR8	18.81	GAR9	18.15
GAR10	20.70	GAR11	15.96	GAR12	23.90
GAR13	29.52	GAR14	14.79	GAR15	29.92
GAR16	21.50	GAR17	15.74	GAR18	19.53
GAR19	20.93	GAR20	68.29	GAR21	23.21
GAR22	15.87	GAR23	17.03	GAR24	17.06
GAR25	38.80	GAR26	19.64	GAR27	21.60
GAR28	18.10	GAR29	17.51	GAR30	18.51
GAR31	13.58	GAR32	5.94	GAR33	10.93
GAR34	23.95	GAR35	16.38	GAR36	23.56
GAR37	8.47	GAR38	22.80	GAR39	5.71
GAR40	17.27	GAR41	16.70	GAR42	16.01
GAR43	30.81	GAR44	23.53	GAR45	15.41
GAR46	18.05	GAR47	35.63	GAR48	17.26
GAR49	20.71	GAR50	19.88	GAR51	17.92
GAR52	14.75	GAR53	16.52	GAR54	25.82
GAR55	45.73	OTH1	6.59	OTH2	8.26
OTH3	4.64	OTH4	11.07	OTH5	10.05
OTH6	4.00	OTH7	7.70	OTH8	7.76
OTH9	37.71	OTH10	5.91	OTH11	15.39
OTH12	6.10	OTH13	11.67	OTH14	9.40
OTH15	14.04	OTH16	4.76	OTH17	5.70
OTH18	14.74	OTH19	9.84	OTH20	8.68
OTH21	6.27				

Table F.2. Workloads and numbers of mechanics in existing configuration.

Facility	Estimated Workload	actual # of mechanics	theoretical # of mechanics
Winchester	114.7	10	10.5
Brookfield	64.3	5.75	5.9
Waterbury	84.2	10	7.7
Darien (Norwalk)	95.0	6.5	8.7
Milford	117.1	10.5	10.7
East Haven	99.8	11	9.2
Wethersfield	196.7	18	18.0
East Granby	116.3	8	10.7
Higganum	96.9	9	8.9
West Willington	92.6	7.5	8.5
Putnam	68.8	7.5	6.3
Lisbon	88.1	7.5	8.1
Old Saybrook	99.1	11	9.1
	------	------	
	1333.6	122.25	

Dividing the total workload shown in Table F.2 by the total number of mechanics results in a ratio of 10.91. Dividing the estimated workloads by this ratio provides the "theoretical" number of mechanics we would expect to see at each facility if mechanics were distributed in proportion to workload. The fact that the theoretical values in Table F.2 are close to the actual values lends support to the use of the estimated workloads as a basis for distributing workers in alternative configurations.

Now let us consider the facilities' workloads in the recommended configurations. Tables F.3 and F.4 show the new mechanics' workloads at facilities for the ten facility and eleven facility options, respectively. Also shown in the tables are proposed numbers of mechanics, which are based on the same ratio of 10.91 used to establish the theoretical values in Table F.2.

Table F.3. Workloads and proposed number of mechanics for the recommended ten facility option.

Facility	Estimated Workload	proposed # of mechanics	change from current system
Winchester	133.5	12.2	+ 2.2
Waterbury	129.6	11.9	+ 1.9
Darien	95.0	8.7	+ 2.2
Milford	178.1	16.3	+ 5.8
Wethersfield	251.6	23.1	+ 5.1
East Granby	116.3	10.6	+ 2.6
West Willington	92.6	8.5	+ 1.0
Putnam	68.8	6.3	- 1.2
Lisbon	118.9	10.9	+ 3.4
Old Saybrook	149.2	13.7	+ 2.7
	------	------	------
	1333.6	122.2	+ 25.7

Table F.4. Workloads and proposed number of mechanics for the recommended eleven facility option.

Facility	Estimated Workload	proposed # of mechanics	change from current system
Winchester	133.5	12.2	+ 2.2
Waterbury	82.8	7.6	- 2.4
Darien	115.7	10.6	+ 4.1
Milford	143.2	13.1	+ 2.6
East Haven	117.3	10.8	- 0.2
Wethersfield	189.0	17.3	- 0.7
East Granby	116.3	10.7	+ 2.7
West Willington	108.6	10.0	+ 2.5
Putnam	68.8	6.3	- 1.2
Lisbon	118.9	10.9	+ 3.4
Old Saybrook	139.3	12.8	+ 1.8
	------	------	------
	1333.6	122.2	+ 14.8

Also shown in Tables F.3 and F.4 are changes in numbers of mechanics at each facility. These represent the difference between the proposed numbers and the actual numbers presented in Table F.2. In both options, the sums of the changes (i.e. 25.7 and 14.8) equal the total number of mechanics currently employed at the facilities that are closed in the respective options. Thus, the system-wide total number of mechanics remains unchanged in both cases.

The weighted average total number of mechanics is 122.25. Since this average includes seven grade 3 mechanics with weights of .75 and eight grade 2 mechanics with weights of .5, the actual number of mechanics in the existing system is 128. Considering that there are 168 work bays in the existing system, it is clear that there is a relatively high work bay to mechanic ratio (i.e. 1.31 bays/mechanic). The proposed ten facility option, with 142 bays, lowers this ratio to 1.11 bays/mechanic. The eleven facility option, with 146 bays, has an associated ratio of 1.14. Based on the proposed configurations and the recommended number of mechanics at the facilities, the minimum ratio of bays/mechanic at any facility would be 0.92 at Milford in the ten facility option. No other facility in either recommended option has a bays/mechanic ratio of less than one. Recalling that equipment in categories 4 and 5 do not require full bays when being repaired, ratios of bays to mechanics which are slightly less than one do not present a problem. Also to be considered is the fact that multiple mechanics might work on the same piece of equipment at the same time, so that one full bay per mechanic is not required.

This concludes the discussion of the methods proposed for the reassignment of mechanics. It should be noted that the total number of mechanics in the repair system may have changed since September, which would affect the reassignments being proposed for the recommended options. Given the workload values presented in Tables F.3 and F.4, new proposed numbers of mechanics could be easily developed for either option based on an updated (total workload) / (total mechanics) ratio. Therefore, much of the information presented in this Appendix can be used to help establish reassignments, even if data regarding the number of mechanics has changed.

APPENDIX G. SOLUTION SUMMARY PAGES

This appendix presents solution summary pages for the runs described in Section IV. The run titles shown on the solution summary pages indicate the run set and the treatment level(s) of the factor(s) varied. For example, the page with run title "Main, 10" summarizes the solution from the main run set when the number of facilities was fixed at ten. For the constrained run set, the run titles start with WETH, EHAV or EHAV/WETH. As described in Section IV, these correspond to the constraints that were added in that run set. For the cost and demand sensitivity run sets, the run titles correspond directly to the factors varied in those run sets. Below the title, each solution summary page includes a description of the scenario upon which the solution is based.

The diagram presented with each solution summary shows the assignments of garages to repair facilities. Each enclosure in the diagram contains exactly one repair facility that the model selected to remain open. All garages within an enclosure are assigned to that open facility. Partial assignments of a garage to two facilities are indicated by having two enclosures pass through the same garage, and the fraction of work assigned to one of the two facilities is indicated near the garage.

Above the diagram is information related to which facilities were closed and which were expanded. Also shown is the optimal objective function value, which is an annual cost figure in thousands of dollars.

Besides the total cost of the solution, it is also important to know how the solution compares to the existing system used by ConnDOT. For this, the optimal 13-facility solution under the same scenario is used as a basis for comparison.

On each solution summary, cost changes relative to the optimal 13-facility solution are broken down based on overhead costs, transportation costs, and expansion costs. The net present value of the total savings, which is based on a 20-year horizon and a 7.125 % interest rate, is also shown. A final entry expresses the savings from the solution as a percentage of the savings offered by the optimal solution to the version of the problem which has no restrictions.

To avoid redundancy, solution summary pages are not presented for the constrained runs that result in solutions which are identical to other solutions. The values shown in Table 5 in Section IV can be used to identify the runs that result in identical solutions. For example, Main, 11 and WETH, 11 both show the same savings in Table 5, indicating that those scenarios result in the same solution. Therefore, a solution summary page labelled WETH, 11 is not presented in this appendix.

SOLUTION SUMMARY PAGE   Run title: Main, unrestricted

Scenario

Overhead costs: Normal   Transportation costs: Normal

Demand level: Normal   # of facilities: unrestricted

Solution

Facilities closed: Brookfield, East Haven, Higganum, East Granby, Putnam, Darien.

Facilities expanded: Waterbury, Wethersfield, Milford.
(# of bays added) (+4.4) (+10) (+5.6)

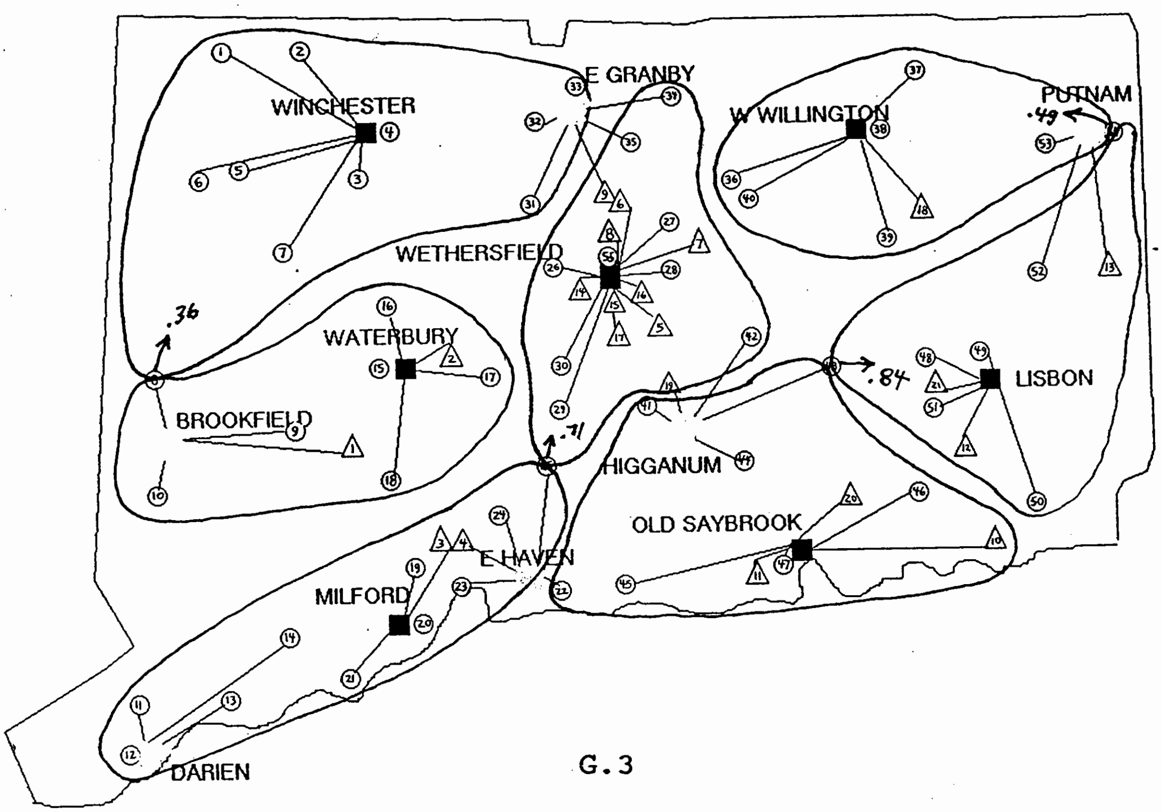
Total annualized cost
(in thousands of dollars): 3441.06

Annualized cost components relative to optimal 13-facility solution (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-1433.4	+575.8	+179.8	-677.8

Net present value of savings: $ 7.1 million

Savings compared to those offered
by optimal, unrestricted solution: 100 %



SOLUTION SUMMARY PAGE   Run title: Main, 8

Scenario

Overhead costs: Normal   Transportation costs: Normal

Demand level: Normal   # of facilities: 8

Solution

Facilities closed: Brookfield, East Haven, Higganum,
East Granby, Putnam.

Facilities expanded: Waterbury, Wethersfield.
(# of bays added) (+4.4) (+10)

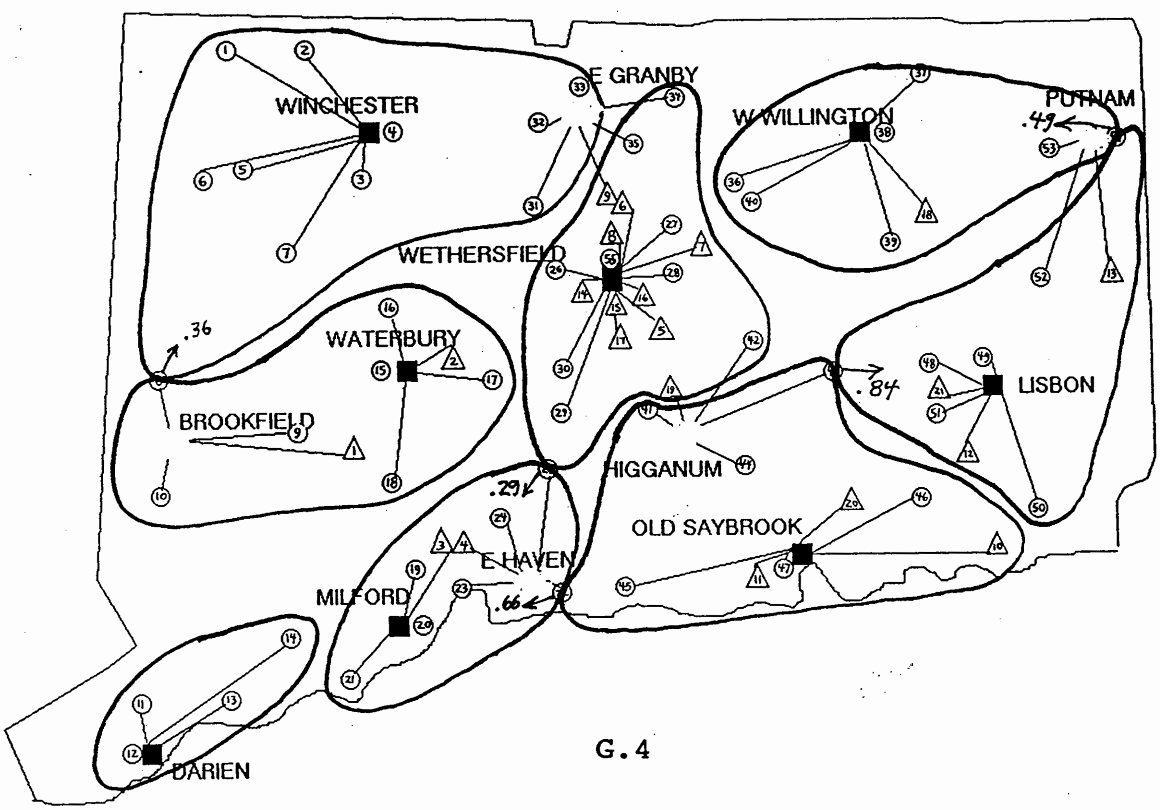
Total annualized cost
(in thousands of dollars): 3474.63

Annualized cost components relative to optimal 13-facility solution (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-1196.9	+424.3	+128.3	-644.3

Net present value of savings: $ 6.8 million

Savings compared to those offered
by optimal, unrestricted solution: 95 %



SOLUTION SUMMARY PAGE Run title: Main, 9

Scenario

Overhead costs: Normal Transportation costs: Normal

Demand level: Normal # of facilities: 9

Solution

Facilities closed: Brookfield, East Haven, Higganum, East Granby.

Facilities expanded: Waterbury, Wethersfield.
(# of bays added) (+4.4) (+10)

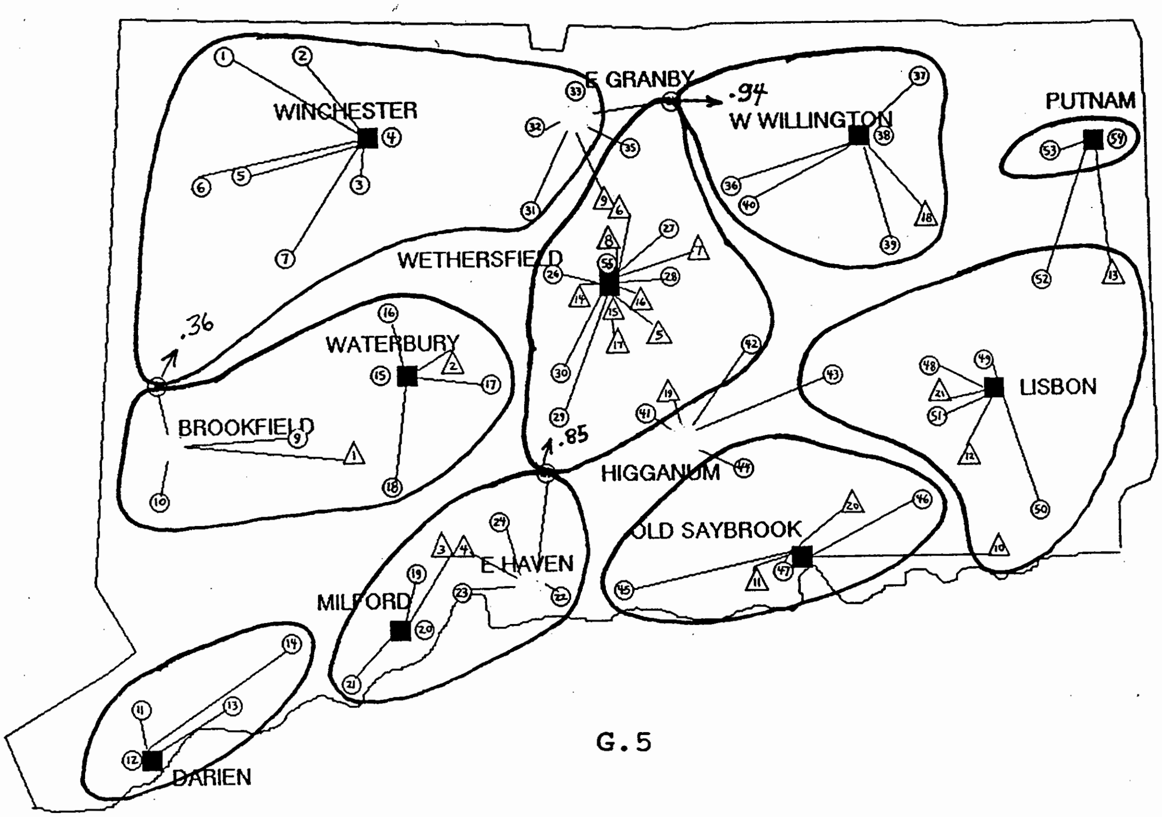
Total annual cost
(in thousands of dollars): 3559.02

Annualized cost components relative to optimal 13-facility solution (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-1012.7	+324.5	+128.3	-559.9

Net present value of savings: $ 5.9 million

Savings compared to those offered
by optimal, unrestricted solution: 83 %



SOLUTION SUMMARY PAGE Run title: Main, 10

Scenario

Overhead costs: Normal Transportation costs: Normal

Demand level: Normal # of facilities: 10

Solution

Facilities closed: Brookfield, East Haven, Higganum

Facilities expanded: Waterbury, Wethersfield.
(# of bays added) (+3.5) (+8.6)

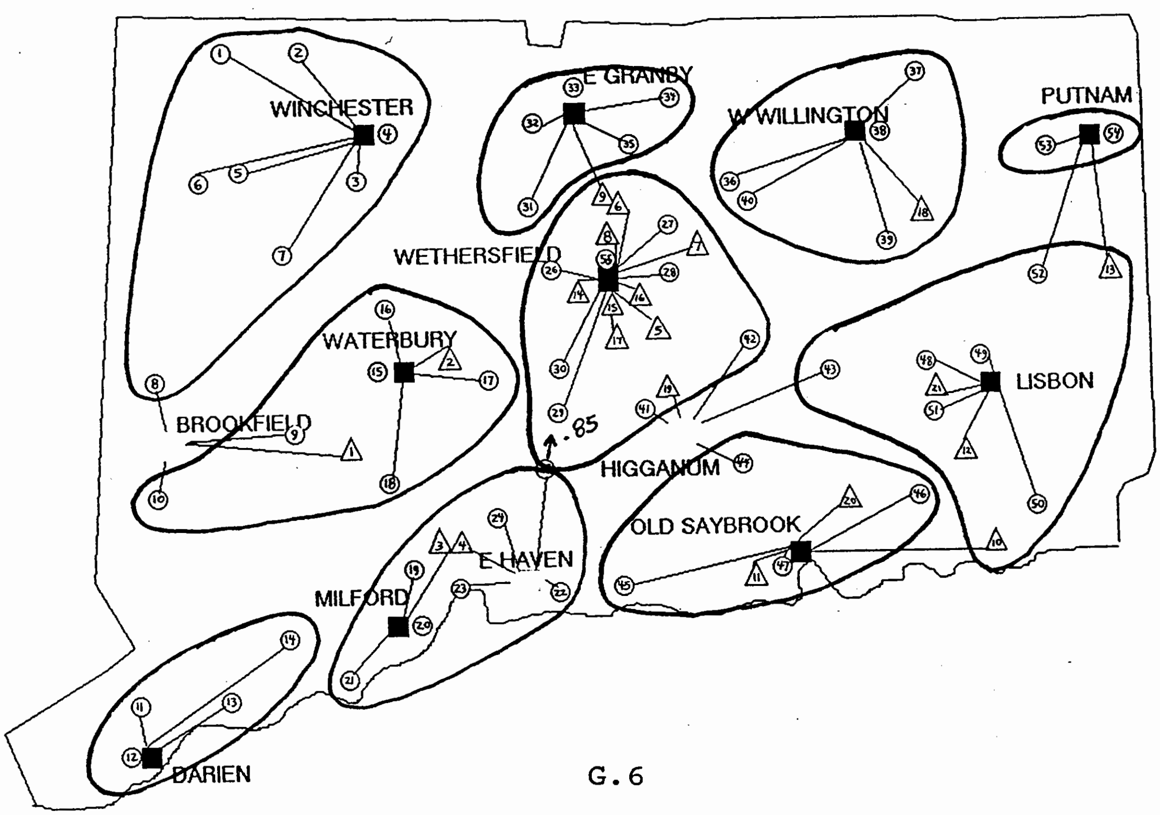
Total annualized cost
(in thousands of dollars): 3658.26

Annualized cost components relative to optimal 13-facility solution (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-795.5	+225.2	+109.7	-460.6

Net present value of savings: $ 4.8 million

Savings compared to those offered
by optimal, unrestricted solution: 68 %



SOLUTION SUMMARY PAGE   Run title: Main, 11

Scenario

Overhead costs: Normal   Transportation costs: Normal

Demand level: Normal   # of facilities: 11

Solution

Facilities closed: Brookfield, East Haven.

Facilities expanded: Waterbury.
(# of bays added) (+3.5)

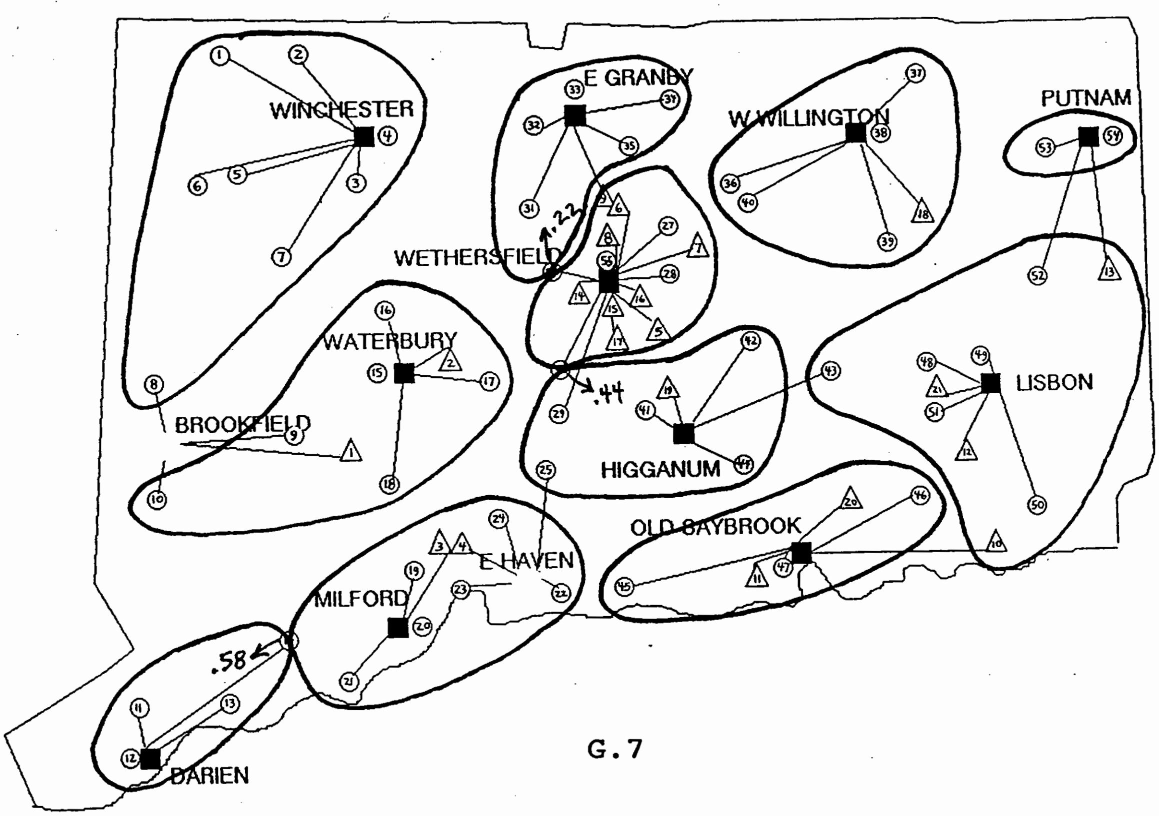
Total annualized cost
(in thousands of dollars): 3785.34

Annualized cost components relative to optimal 13-facility solution (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-566.9	+199.0	+34.3	-333.6

Net present value of savings: $ 3.5 million

Savings compared to those offered by optimal, unrestricted solution: 49 %



SOLUTION SUMMARY PAGE Run title: Main, 12

Scenario

Overhead costs: Normal Transportation costs: Normal

Demand level: Normal # of facilities: 12

Solution

Facilities closed: East Haven.

Facilities expanded: None
(# of bays added)

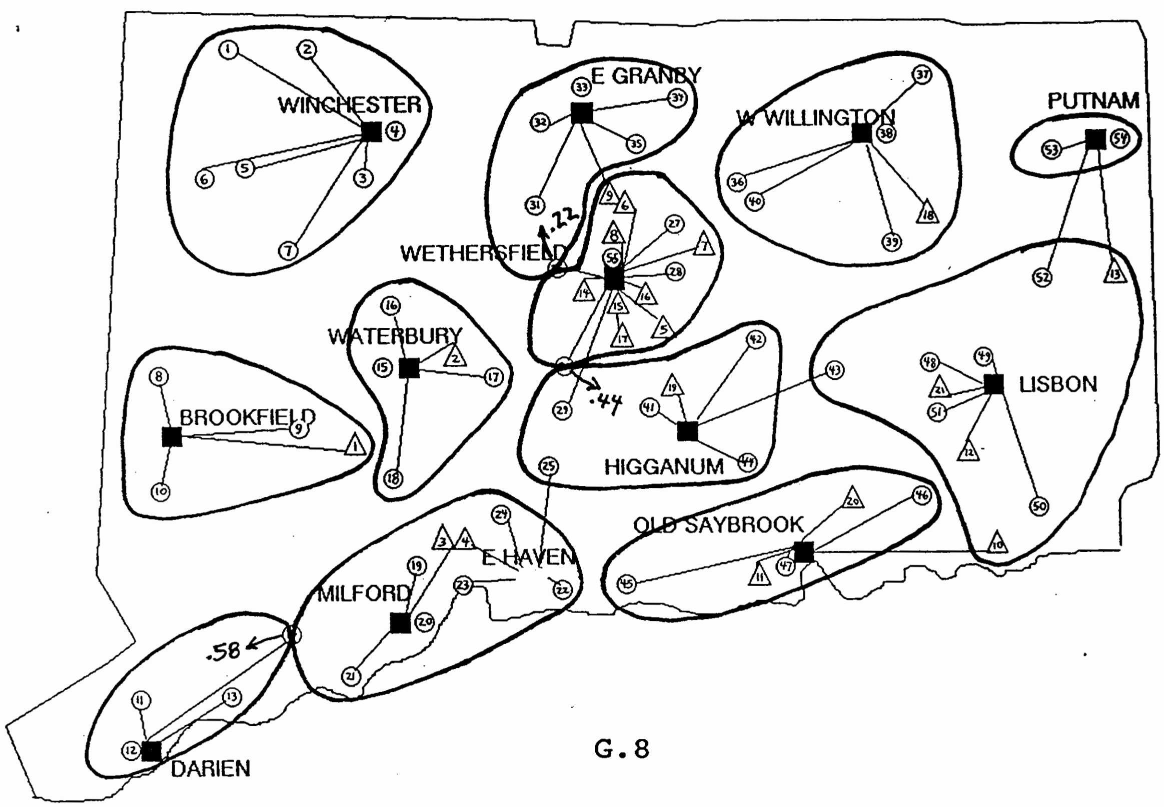
Total annualized cost
(in thousands of dollars): 3930.95

Annualized cost components relative to optimal 13-facility solution (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-285.5	+97.5		-188.0

Net present value of savings: $ 2.0 million

Savings compared to those offered
by optimal, unrestricted solution: 28 %



SOLUTION SUMMARY PAGE   Run title: Main, 13

Scenario

Overhead costs: Normal   Transportation costs: Normal

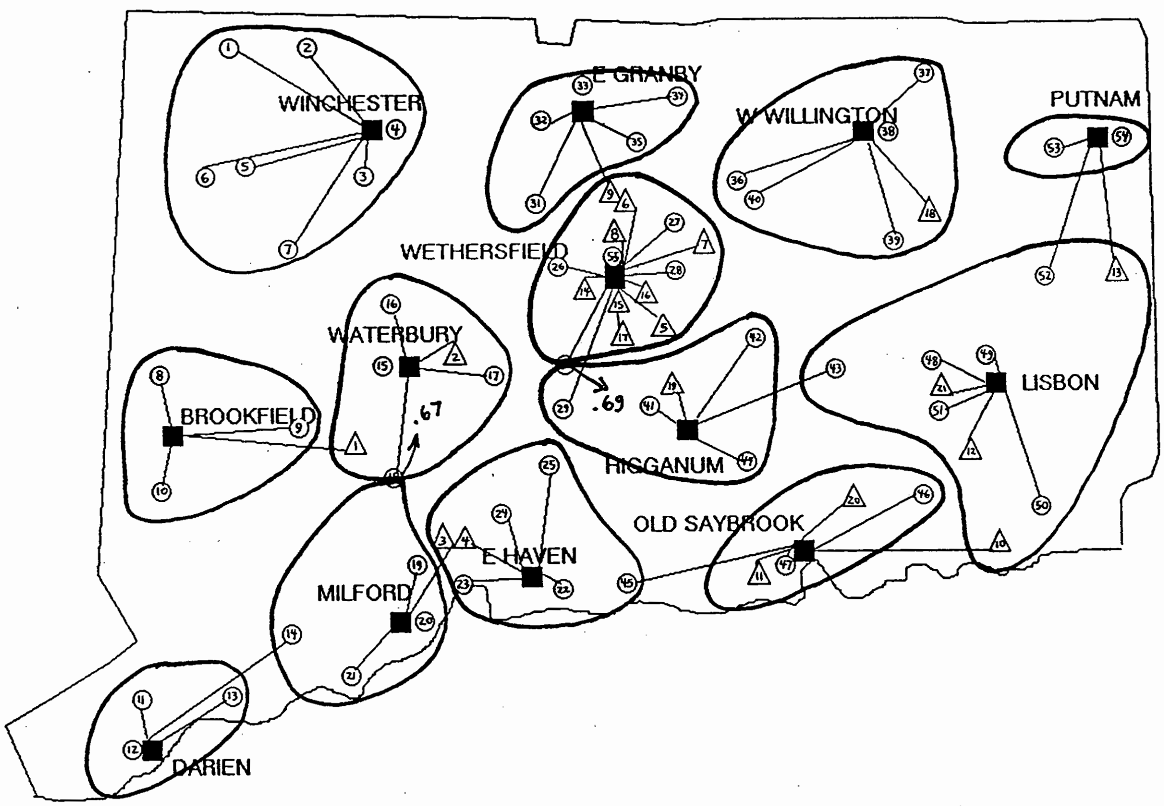
Demand level: Normal   # of facilities: 13

Solution

Facilities closed: None

Facilities expanded: None
(# of bays added)

Total annualized cost
(in thousands of dollars): 4118.87



SOLUTION SUMMARY PAGE   Run title: WETH, unrestricted

Scenario

Overhead costs: Normal   Transportation costs: Normal
Demand level: Normal   # of facilities: unrestricted
No expansion permitted at Wethersfield

Solution

Facilities closed: Brookfield, East Haven, Higganum, East Granby, Putnam, Darien.

Facilities expanded:	Waterbury,	W. Willington,	Milford.
(# of bays added)	(+8.1)	(+2.3)	(+9)

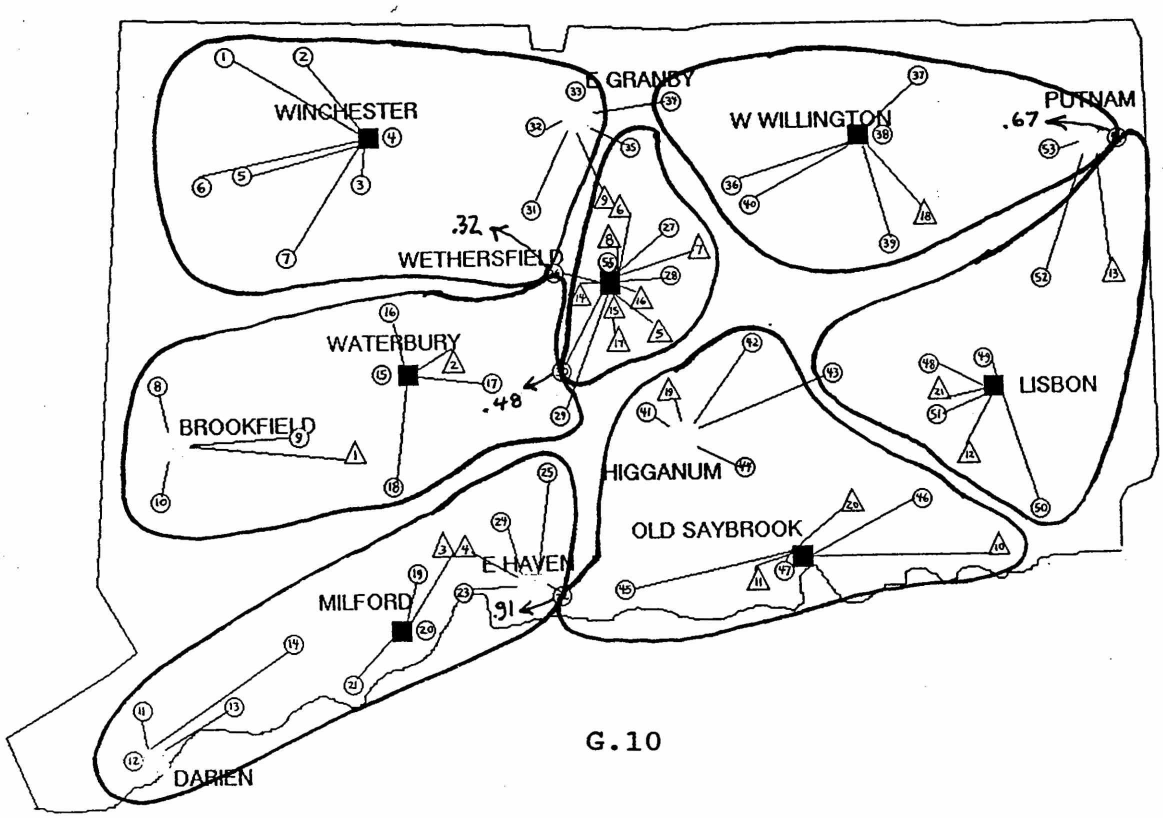
Total annualized cost
(in thousands of dollars): 3516.53

Annualized cost components relative to optimal 13-facility solution (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-1433.4	+656.4	+174.7	-602.3

Net present value of savings: $ 6.3 million

Savings compared to those offered
by optimal, unrestricted solution: 89 %



SOLUTION SUMMARY PAGE   Run title: WETH, 8

Scenario

Overhead costs: Normal   Transportation costs: Normal
Demand level: Normal   # of facilities: 8
No expansion permitted at Wethersfield.

Solution

Facilities closed: Brookfield, East Haven, Higganum, East Granby, Putnam.

Facilities expanded:	Waterbury,	Milford,	W. Willington
(# of bays added)	(+8.1)	(+2.5)	(2.3)

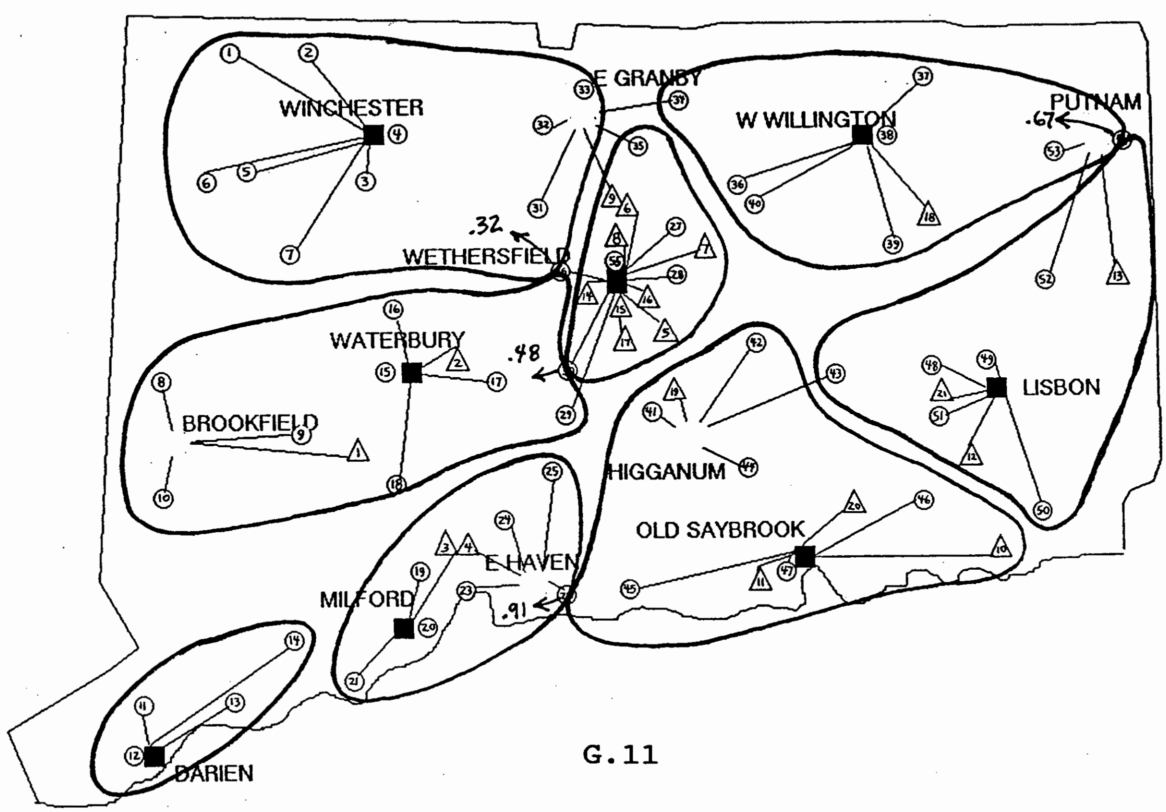
Total annualized cost
(in thousands of dollars): 3555.63

Annualized cost components relative to optimal 13-facility solution (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-1196.9	+511.5	+122.2	-563.2

Net present value of savings: $ 5.9 million

Savings compared to those offered
by optimal, unrestricted solution: 83 %



SOLUTION SUMMARY PAGE Run title: WETH, 9

Scenario

Overhead costs: Normal Transportation costs: Normal
Demand level: Normal # of facilities: 9
No expansion permitted at Wethersfield

Solution

Facilities closed: Brookfield, East Haven, Higganum, Putnam.

Facilities expanded: Waterbury
(# of bays added) (+4.9)

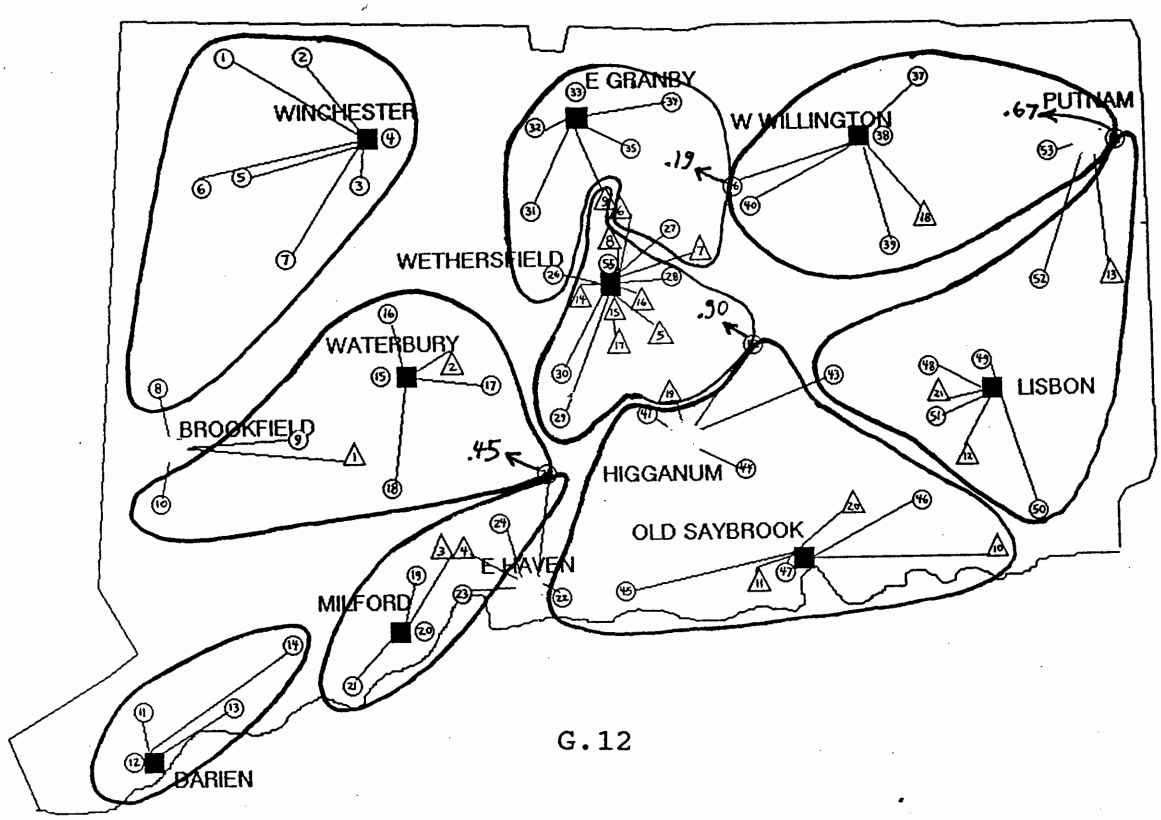
Total annual cost
(in thousands of dollars): 3597.97

Annualized cost components relative to optimal 13-facility solution (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-979.7	+413.2	+45.6	-520.9

Net present value of savings: $ 5.5 million

Savings compared to those offered by optimal, unrestricted solution: 77 %



SOLUTION SUMMARY PAGE   Run title: WETH, 10

Scenario

Overhead costs: Normal   Transportation costs: Normal
Demand level: Normal   # of facilities: 10
No expansion permitted at Wethersfield

Solution

Facilities closed: Brookfield, East Haven, Higganum,

Facilities expanded: Waterbury, Milford.
(# of bays added) (+3.5) (+2)

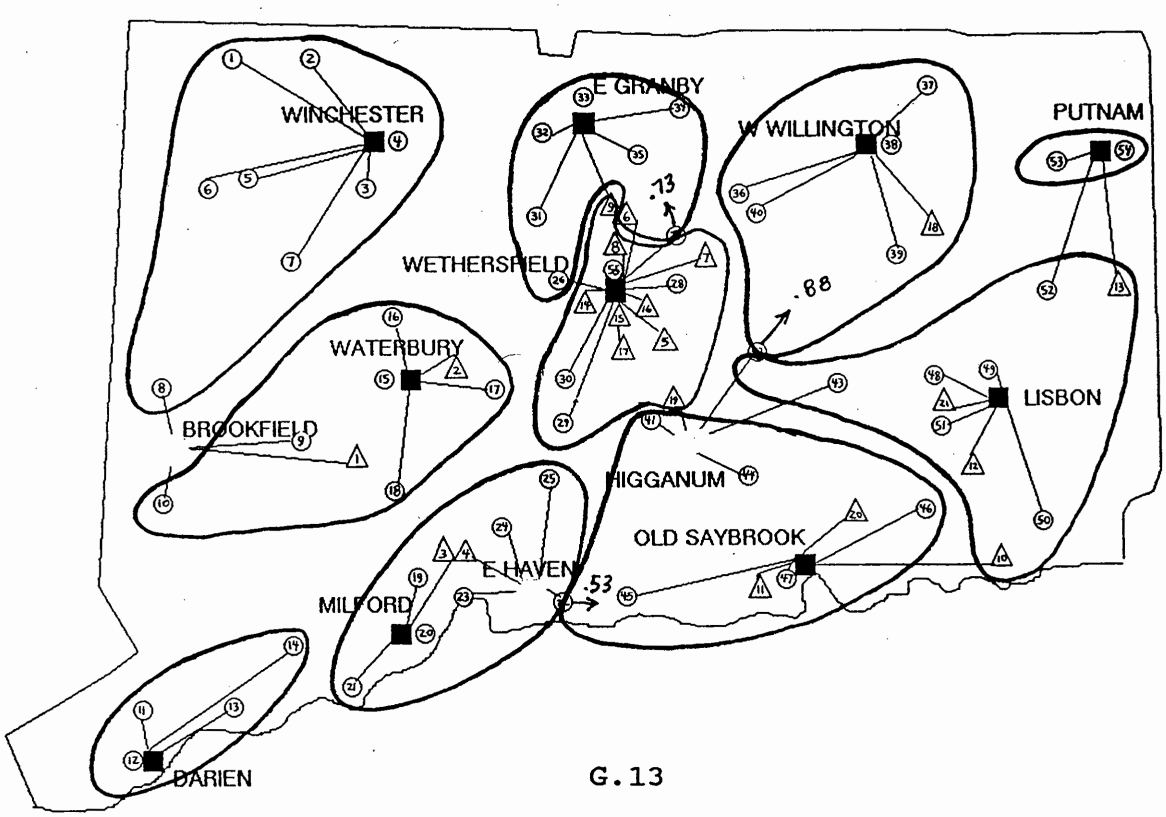
Total annualized cost
(in thousands of dollars): 3682.77

Annualized cost components relative to optimal 13-facility solution (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-795.5	+303.0	+56.4	-436.1

Net present value of savings: $ 4.6 million

Savings compared to those offered
by optimal, unrestricted solution: 64 %



SOLUTION SUMMARY PAGE Run title: EHAV, unrestricted

Scenario

Overhead costs: Normal Transportation costs: Normal
Demand level: Normal # of facilities: unrestricted
East Haven remains open.

Solution

Facilities closed: Brookfield, Higganum, Darien
East Granby, Putnam.

Facilities expanded: Waterbury, Wethersfield
(# of bays added) (+4.4) (+7.9)

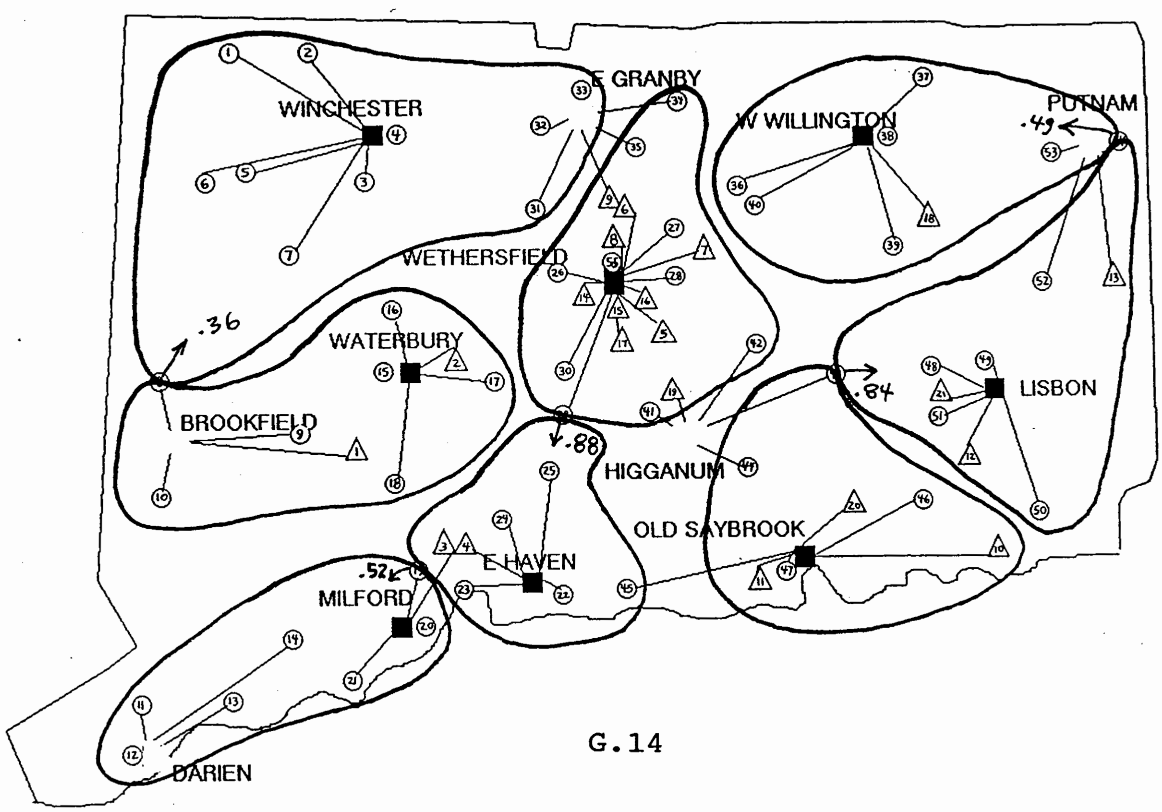
Total annualized cost
(in thousands of dollars): 3563.89

Annualized cost components relative to optimal 13-facility solution (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-1147.9	+481.6	+111.3	-555.0

Net present value of savings: $ 5.8 million

Savings compared to those offered
by optimal, unrestricted solution: 82 %



SOLUTION SUMMARY PAGE   Run title: EHAV, 9

Scenario

Overhead costs: Normal   Transportation costs: Normal
Demand level: Normal   # of facilities: 9
East Haven remains open.

Solution

Facilities closed: Brookfield, East Granby, Higganum, Putnam.

Facilities expanded: Wethersfield
(# of bays added) (+8.9)

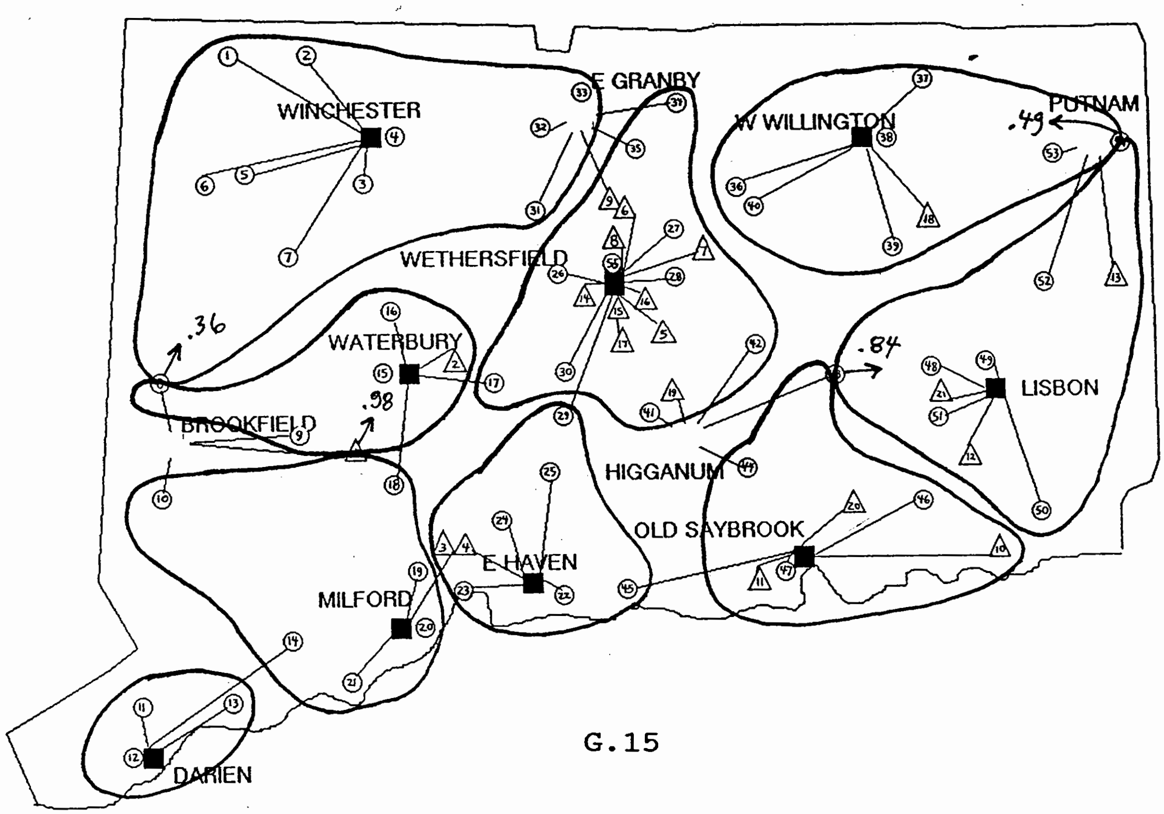
Total annual cost
(in thousands of dollars): 3635.44

Annualized cost components relative to optimal 13-facility solution (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-911.4	+350.1	+77.9	-483.4

Net present value of savings: $ 5.1 million

Savings compared to those offered by optimal, unrestricted solution: 71 %



SOLUTION SUMMARY PAGE Run title: EHAV, 10

Scenario

Overhead costs: Normal Transportation costs: Normal
Demand level: Normal # of facilities: 10
East Haven remains open

Solution

Facilities closed: Brookfield, East Granby, Higganum,

Facilities expanded: Waterbury, Wethersfield.
(# of bays added) (+2) (+7.7)

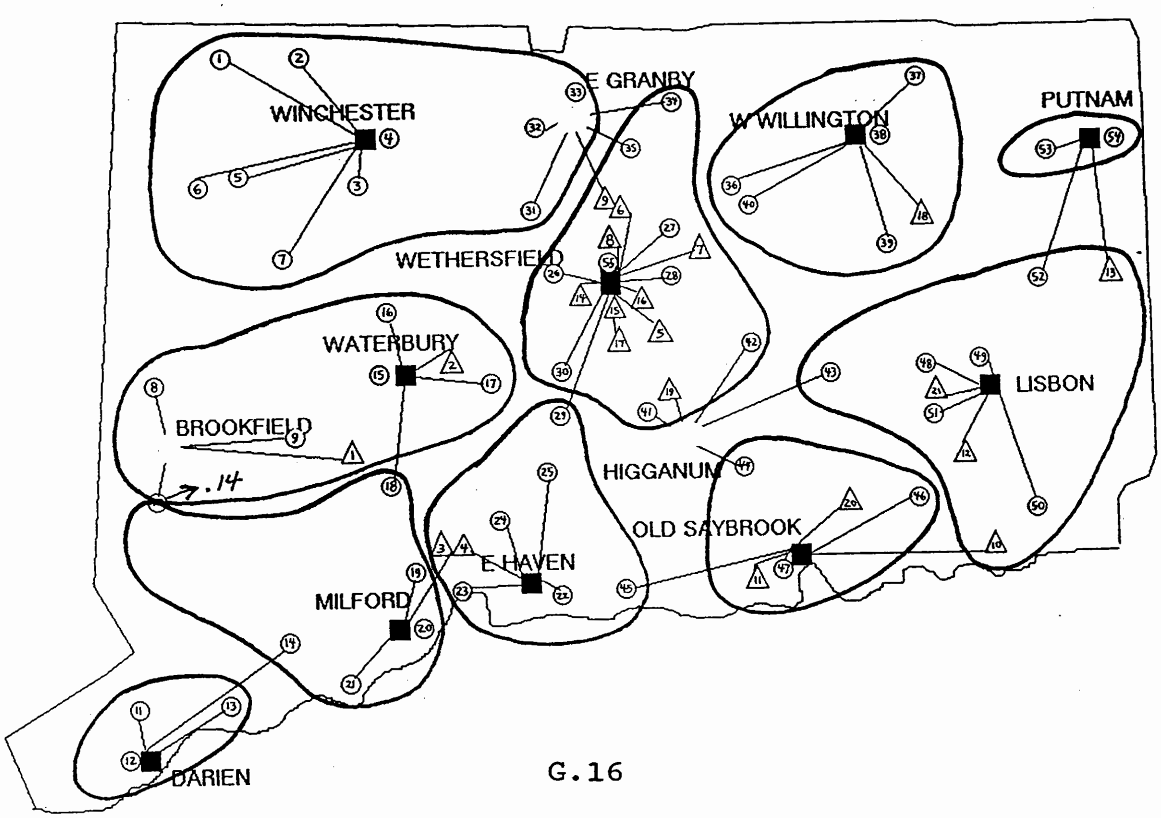
Total annualized cost
(in thousands of dollars): 3722.98

Annualized cost components relative to optimal 13-facility solution (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-727.2	+241.0	+90.3	-395.9

Net present value of savings: $ 4.2 million

Savings compared to those offered by optimal, unrestricted solution: 58 %



SOLUTION SUMMARY PAGE Run title: EHAV, 11

Scenario

Overhead costs: Normal
Demand level: Normal
Transportation costs: Normal
# of facilities: 11
East Haven remains open.

Solution

Facilities closed: Brookfield, Higganum

Facilities expanded: Wethersfield
(# of bays added) (+4.8)

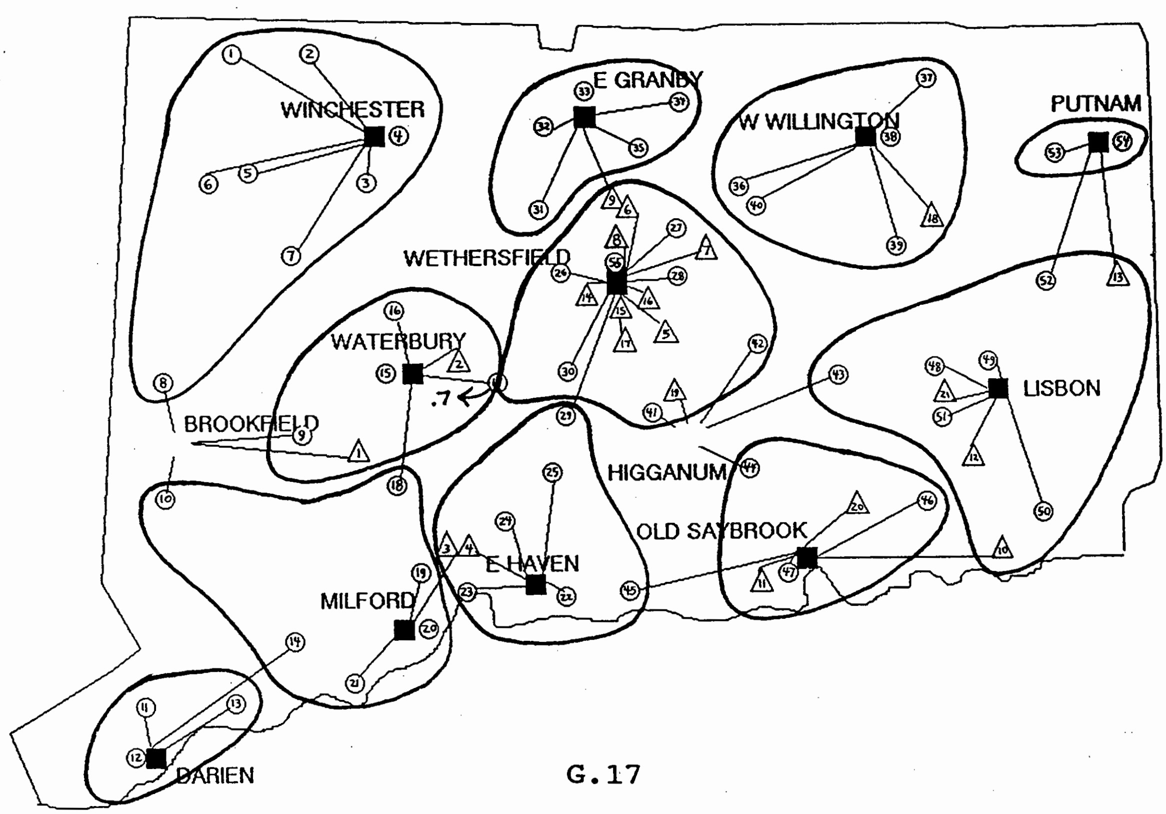
Total annual cost
(in thousands of dollars): 3817.43

Annualized cost components relative to optimal 13-facility solution (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-510.0	+163.8	+44.8	-301.4

Net present value of savings: $ 3.2 million

Savings compared to those offered
by optimal, unrestricted solution: 44 %



SOLUTION SUMMARY PAGE   Run title: EHAV, 12

Scenario

Overhead costs: Normal   Transportation costs: Normal
Demand level: Normal   # of facilities: 12
East Haven remains open

Solution

Facilities closed: Brookfield

Facilities expanded: None.
(# of bays added)

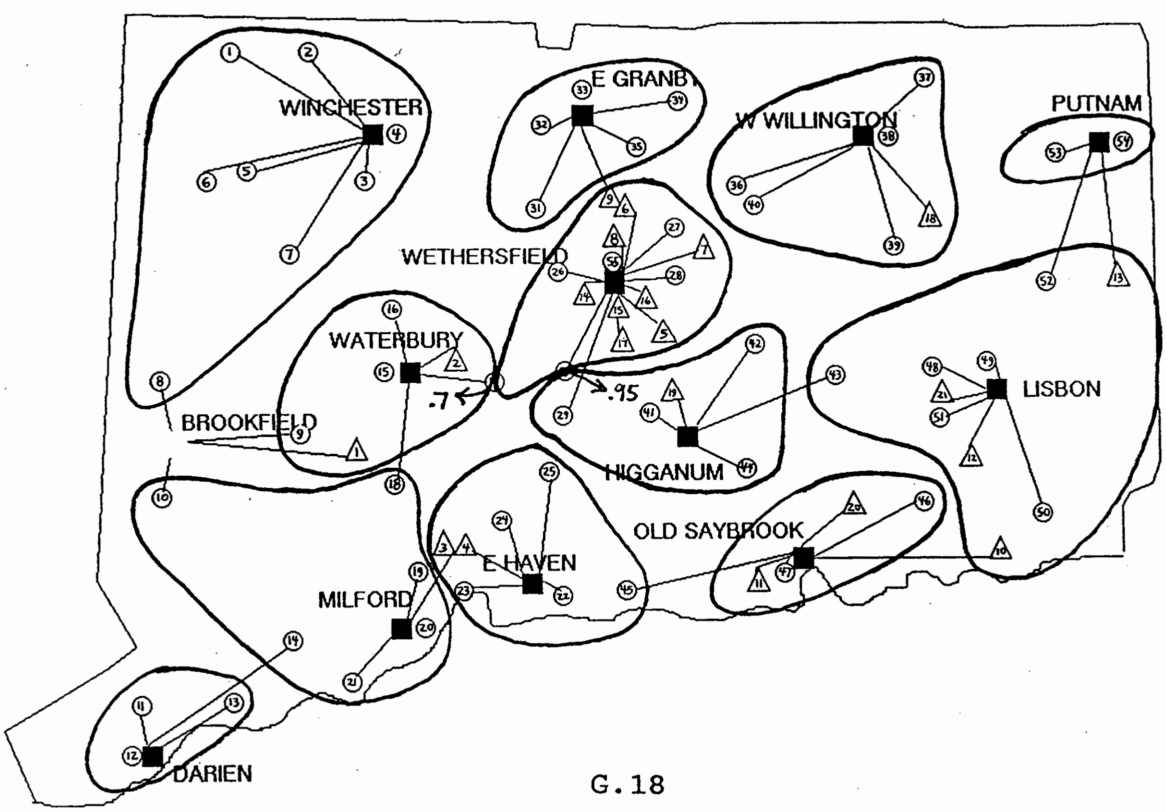
Total annualized cost
(in thousands of dollars): 3965.93

Annualized cost components relative to optimal 13-facility solution (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-281.4	+128.5		-152.9

Net present value of savings: $ 1.6 million

Savings compared to those offered by optimal, unrestricted solution: 23 %



SOLUTION SUMMARY PAGE Run title: EHAV/WETH, unrestricted

Scenario

Overhead costs: Normal Transportation costs: Normal
Demand level: Normal # of facilities: unrestricted
East Haven remains open and no expansion at Wethersfield.

Solution

Facilities closed: Brookfield, Higganum, Darien
East Granby, Putnam.

Facilities expanded: Waterbury, W. Willington
(# of bays added) (+6.7) (+2.3)

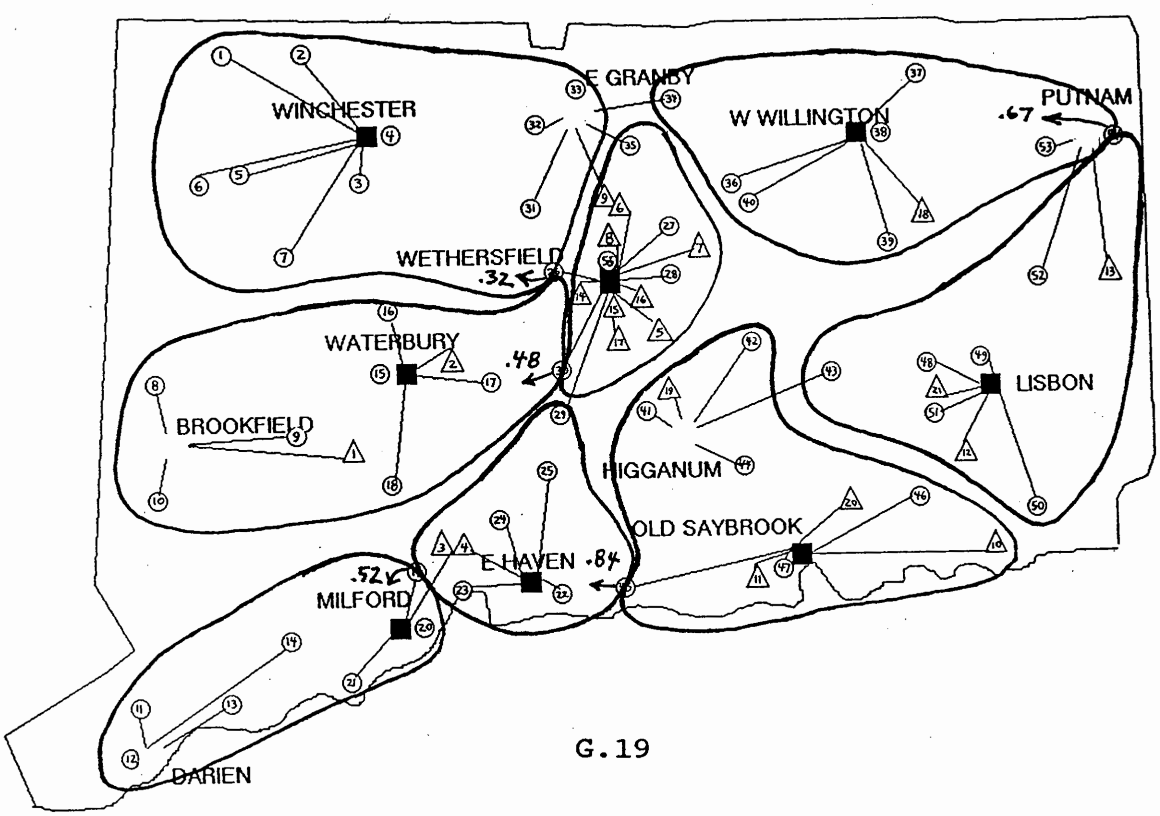
Total annualized cost
(in thousands of dollars): 3622.45

Annualized cost components relative to optimal 13-facility solution (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-1147.9	+566.8	+84.7	-496.4

Net present value of savings: $ 5.2 million

Savings compared to those offered
by optimal, unrestricted solution: 73 %



SOLUTION SUMMARY PAGE   Run title: EHAV/WETH, 9

Scenario

Overhead costs: Normal   Transportation costs: Normal
Demand level: Normal   # of facilities: 9
East Haven remains open and no expansion at Wethersfield.

Solution

Facilities closed: Brookfield, Darien, Higganum, Putnam.

Facilities expanded: Waterbury
(# of bays added) (+3.5)

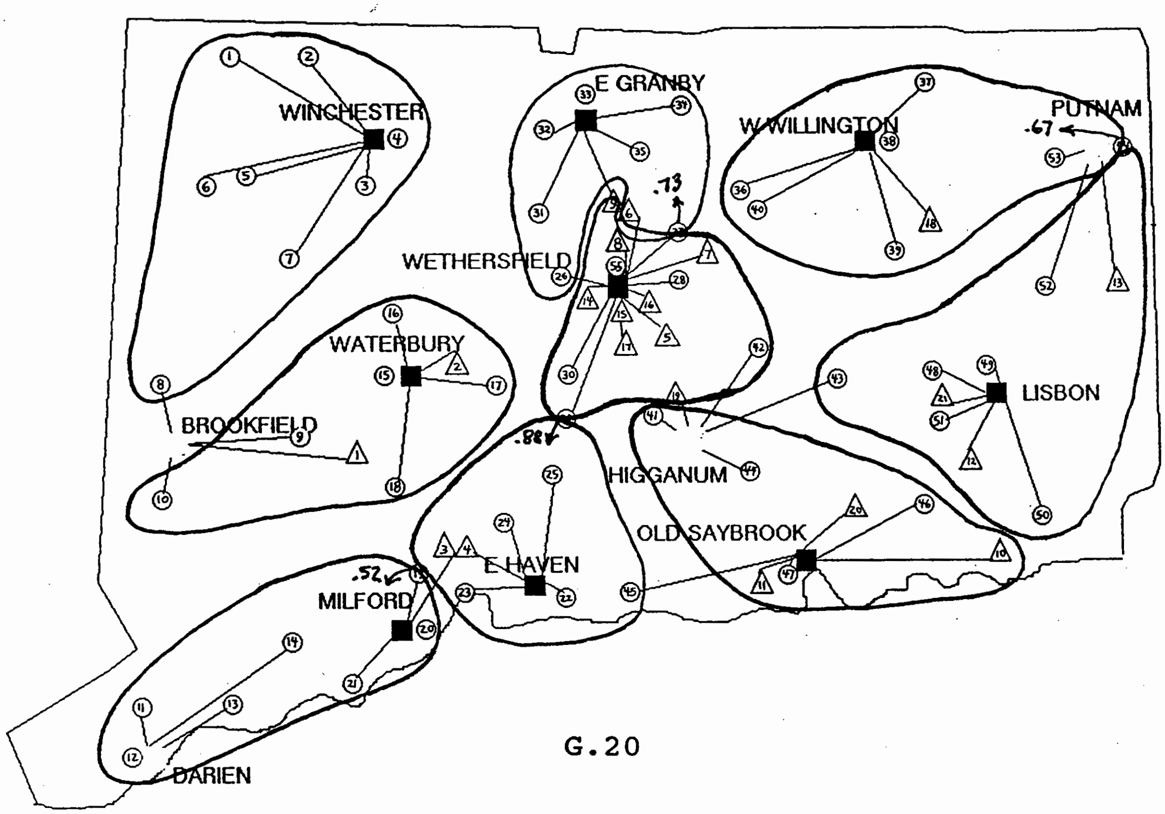
Total annual cost
(in thousands of dollars): 3671.19

Annualized cost components relative to optimal 13-facility solution (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-930.7	+448.7	+34.3	-447.7

Net present value of savings: $ 4.7 million

Savings compared to those offered
by optimal, unrestricted solution: 66 %



SOLUTION SUMMARY PAGE   Run title: EHAV/WETH, 10

Scenario

Overhead costs: Normal   Transportation costs: Normal
Demand level: Normal   # of facilities: 10
East Haven remains open and no expansion at Wethersfield.

Solution

Facilities closed: Brookfield, Putnam, Higganum,

Facilities expanded: None
(# of bays added)

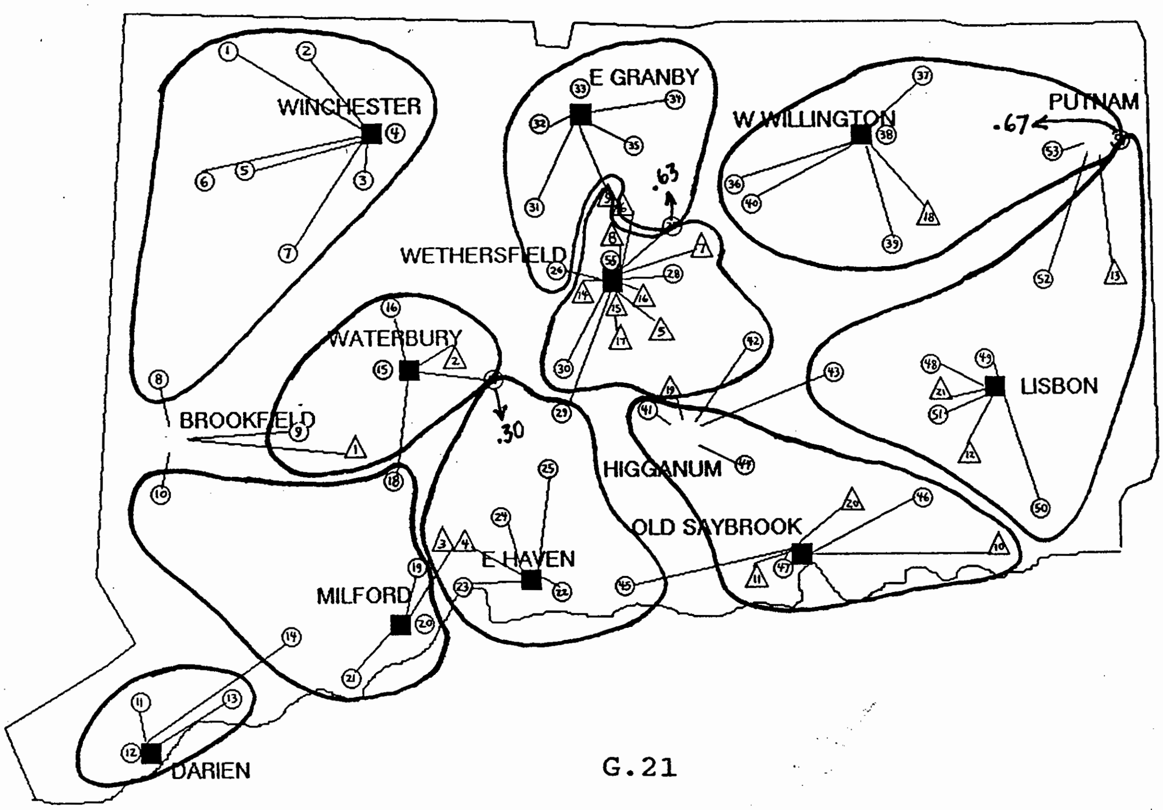
Total annualized cost
(in thousands of dollars): 3739.63

Annualized cost components relative to optimal 13-facility solution (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-694.2	+315.0		-379.2

Net present value of savings: $ 4.0 million

Savings compared to those offered
by optimal, unrestricted solution: 56 %



SOLUTION SUMMARY PAGE   Run title: EHAV/WETH, 11

Scenario

Overhead costs: Normal   Transportation costs: Normal
Demand level: Normal   # of facilities: 11
East Haven remains open and no expansion at Wethersfield.

Solution

Facilities closed: Brookfield, Higganum

Facilities expanded: None
(# of bays added)

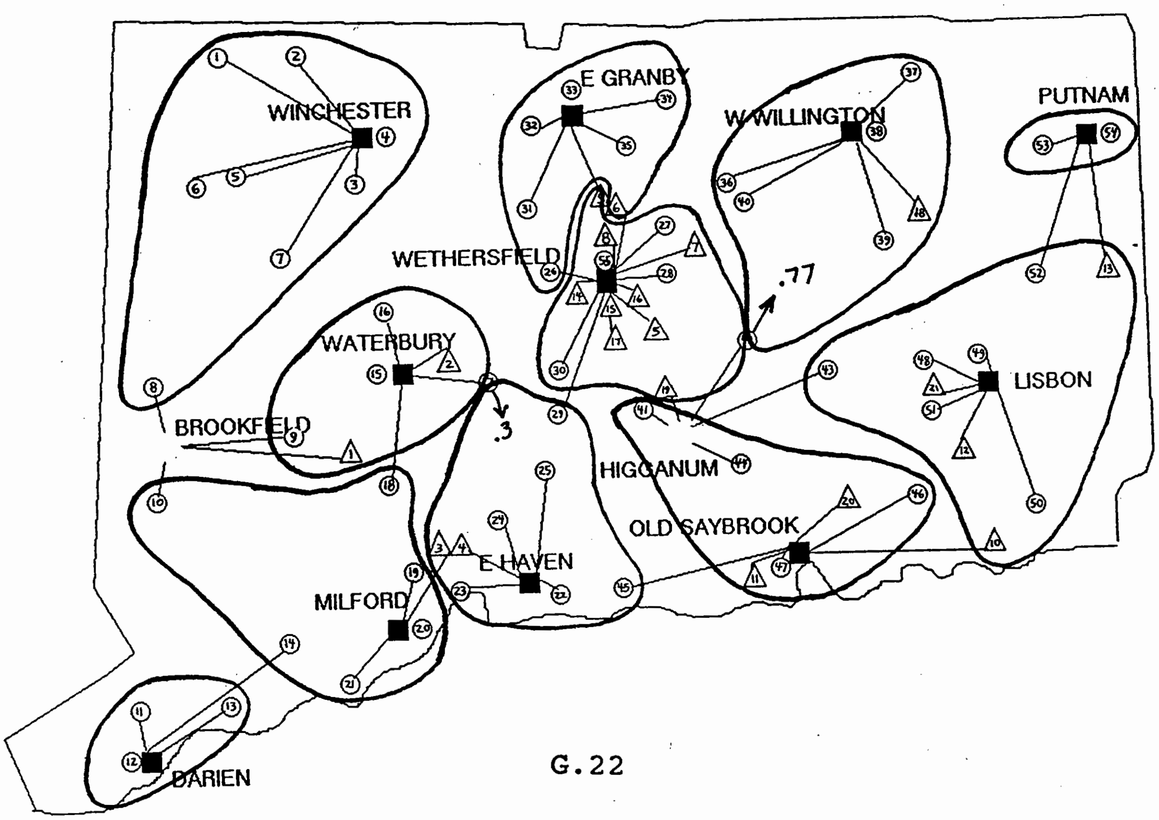
Total annual cost
(in thousands of dollars): 3824.05

Annualized cost components relative to optimal 13-facility solution (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-510.0	+215.2		-294.8

Net present value of savings: $ 3.1 million

Savings compared to those offered
by optimal, unrestricted solution: 43 %



SOLUTION SUMMARY PAGE

Run title:
Cost Sens. (T-20, O+20, unrestricted)

Scenario

Overhead costs: + 20 %   Transportation costs: - 20 %

Demand level: Normal   # of facilities: unrestricted

Solution

Facilities closed: Brookfield, East Haven, Higganum, Lisbon
East Granby, Darien, West Willington

Facilities expanded: Waterbury(+5.4), Wethersfield(+10),
(# of bays added) Milford(+9.1), Old Saybrook (+5.5)

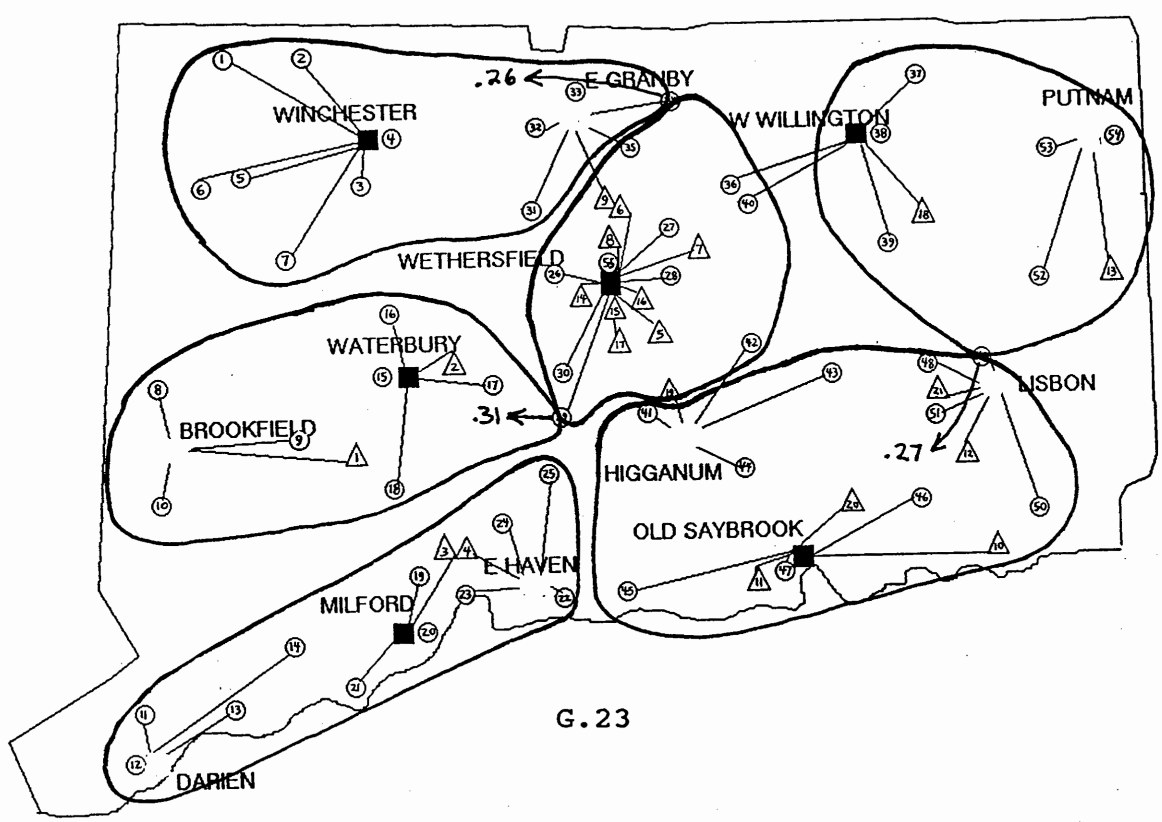
Total annualized cost
(in thousands of dollars): 3330.33

Annualized cost components relative to optimal 13-facility solution (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-2035.7	+643.4	+266.3	-1126.0

Net present value of savings: $ 11.8 million

Savings compared to those offered
by optimal, unrestricted solution: 100 %



SOLUTION SUMMARY PAGE

Run title:
Cost Sens. (T-20, O+20, 10)

Scenario

Overhead costs: + 20 %   Transportation costs: - 20 %

Demand level: Normal   # of facilities: 10

Solution

Facilities closed: Brookfield, East Haven, Higganum

Facilities expanded: Waterbury, Wethersfield
(# of bays added) (+3.5) (+6)

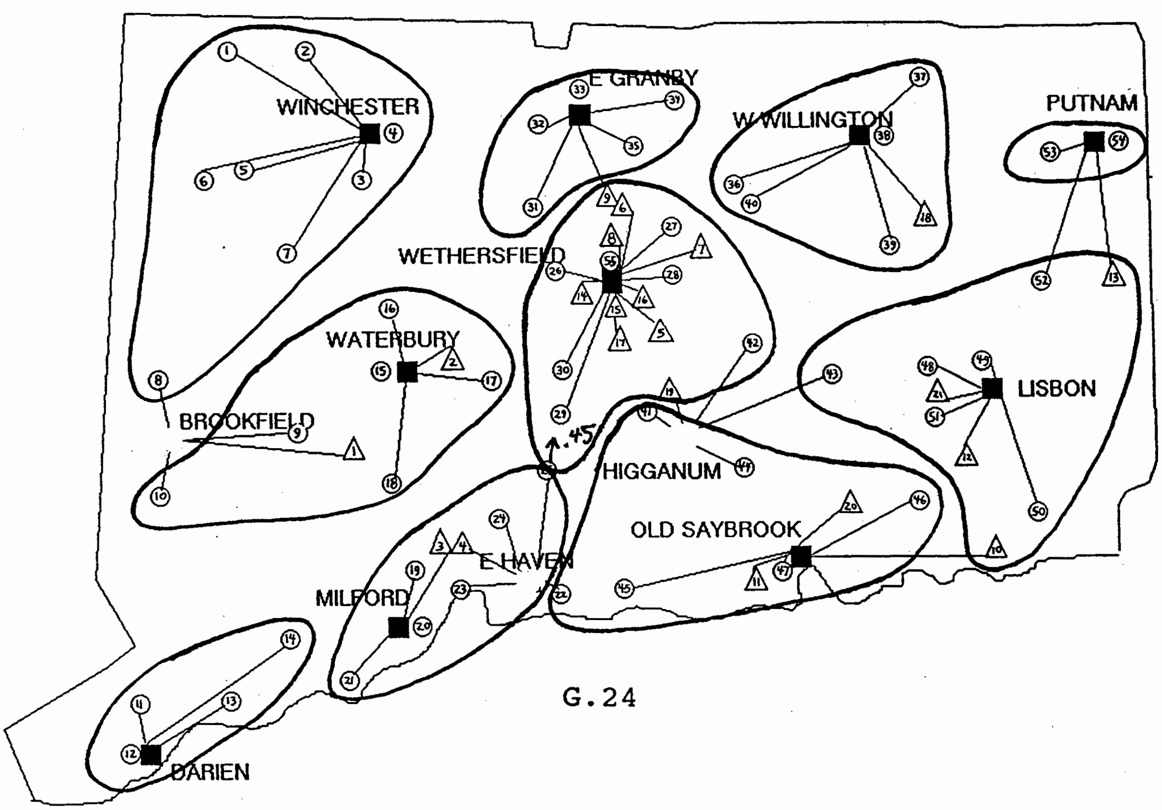
Total annualized cost
(in thousands of dollars): 3789.08

Annualized cost components relative to optimal 13-facility solution (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-954.6	+198.7	+88.7	-677.2

Net present value of savings: $ 7.0 million

Savings compared to those offered
by optimal, unrestricted solution: 59 %



SOLUTION SUMMARY PAGE

Run title:
Cost Sens. (T-20, O+20, 11)

Scenario

Overhead costs: + 20 %   Transportation costs: - 20 %
Demand level: Normal   # of facilities: 11
East Haven remains open, and no expansion at Wethersfield.

Solution

Facilities closed: Brookfield, Higganum

Facilities expanded: None
(# of bays added)

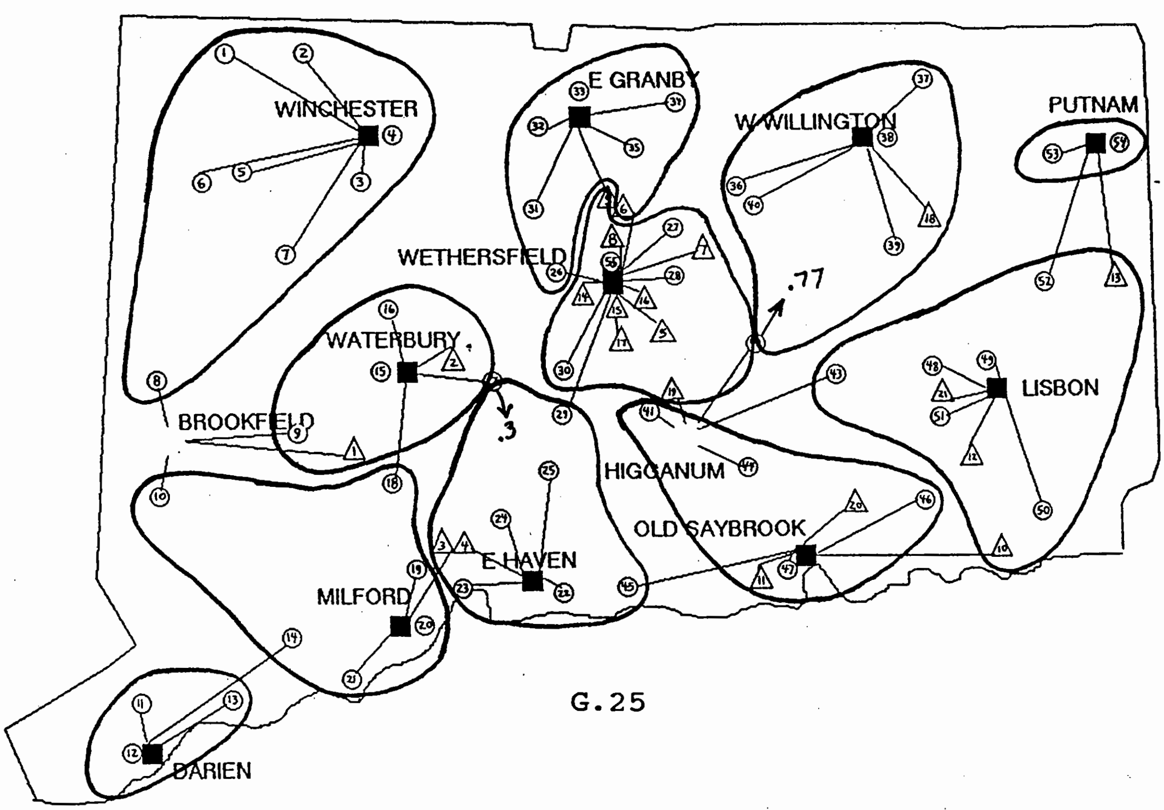
Total annualized cost
(in thousands of dollars): 4016.36

Annualized cost components relative to optimal 13-facility solution (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-612.0	+172.1		-439.9

Net present value of savings: $ 4.6 million

Savings compared to those offered by optimal, unrestricted solution: 39 %



SOLUTION SUMMARY PAGE Run title: Cost Sens. (T-20, O normal, unrestricted)

Scenario

Overhead costs: Normal Transportation costs: - 20 %

Demand level: Normal # of facilities: unrestricted

Solution

Facilities closed: Brookfield, East Haven, Higganum, Darien, Putnam, East Granby

Facilities expanded:	Waterbury,	Wethersfield,	Milford
(# of bays added)	(+4.4)	(+10)	(+5.6)

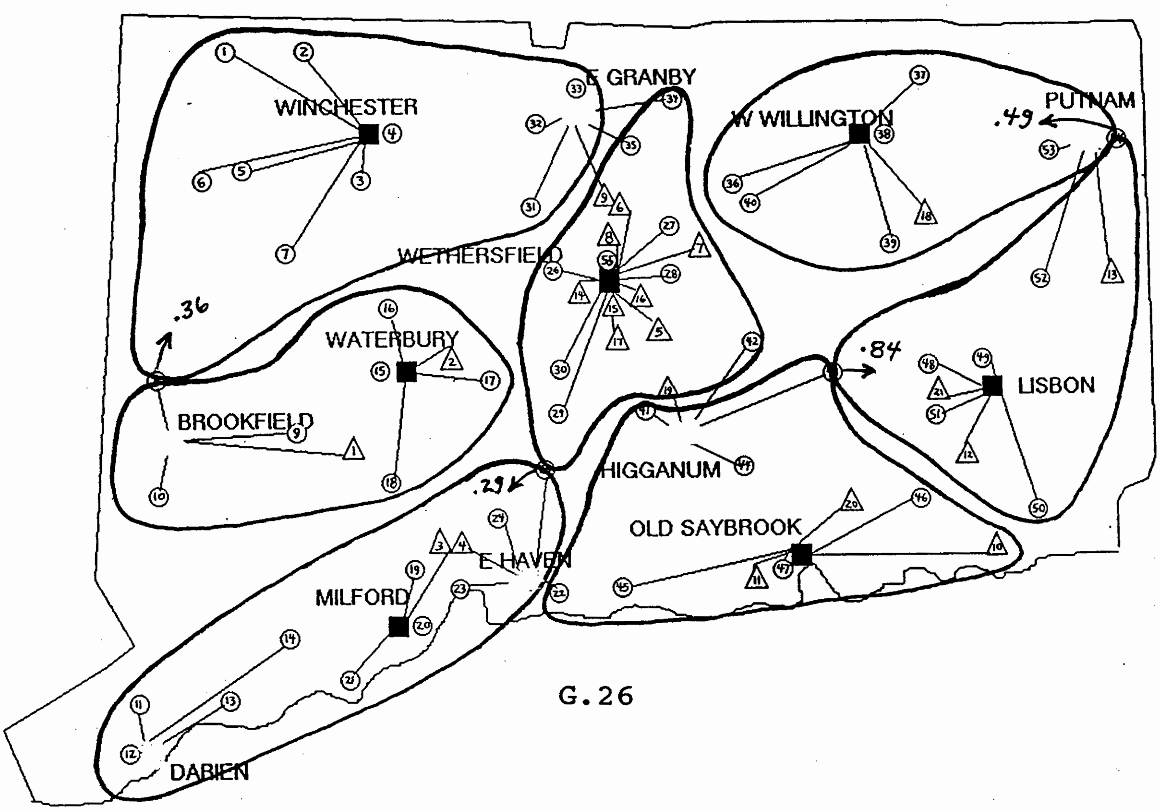
Total annualized cost
(in thousands of dollars): 3083.00

Annualized cost components relative to optimal 13-facility solution (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-1433.4	+461.2	+179.5	-792.7

Net present value of savings: $ 8.3 million

Savings compared to those offered
by optimal, unrestricted solution: 100 %



SOLUTION SUMMARY PAGE

Run title:
Cost Sens. (T-20, O normal, 10)

Scenario

Overhead costs: Normal — Transportation costs: - 20 %

Demand level: Normal — # of facilities: 10

Solution

Facilities closed: Brookfield, East Haven, Higganum

Facilities expanded: Waterbury, Wethersfield
(# of bays added) (+3.5) (+6)

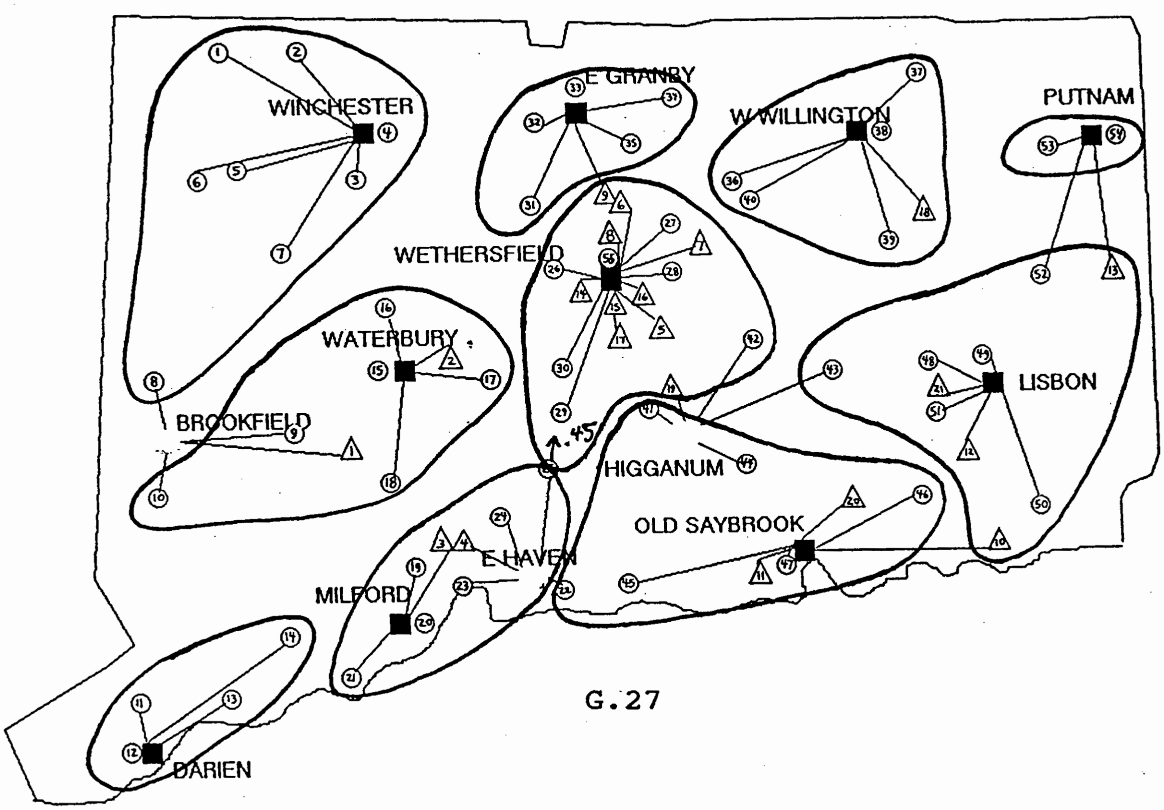
Total annualized cost
(in thousands of dollars): 3367.62

Annualized cost components relative to optimal 13-facility solution (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-795.5	+198.9	+88.5	-508.1

Net present value of savings: $ 5.3 million

Savings compared to those offered
by optimal, unrestricted solution: 64 %



SOLUTION SUMMARY PAGE

Run title:
Cost Sens. (T-20, 0 normal, 11)

<u>Scenario</u>

Overhead costs: Normal   Transportation costs: - 20 %
Demand level: Normal   # of facilities: 11
East Haven remains open, and no expansion at Wethersfield.

<u>Solution</u>

Facilities closed: Brookfield, Higganum

Facilities expanded: None
(# of bays added)

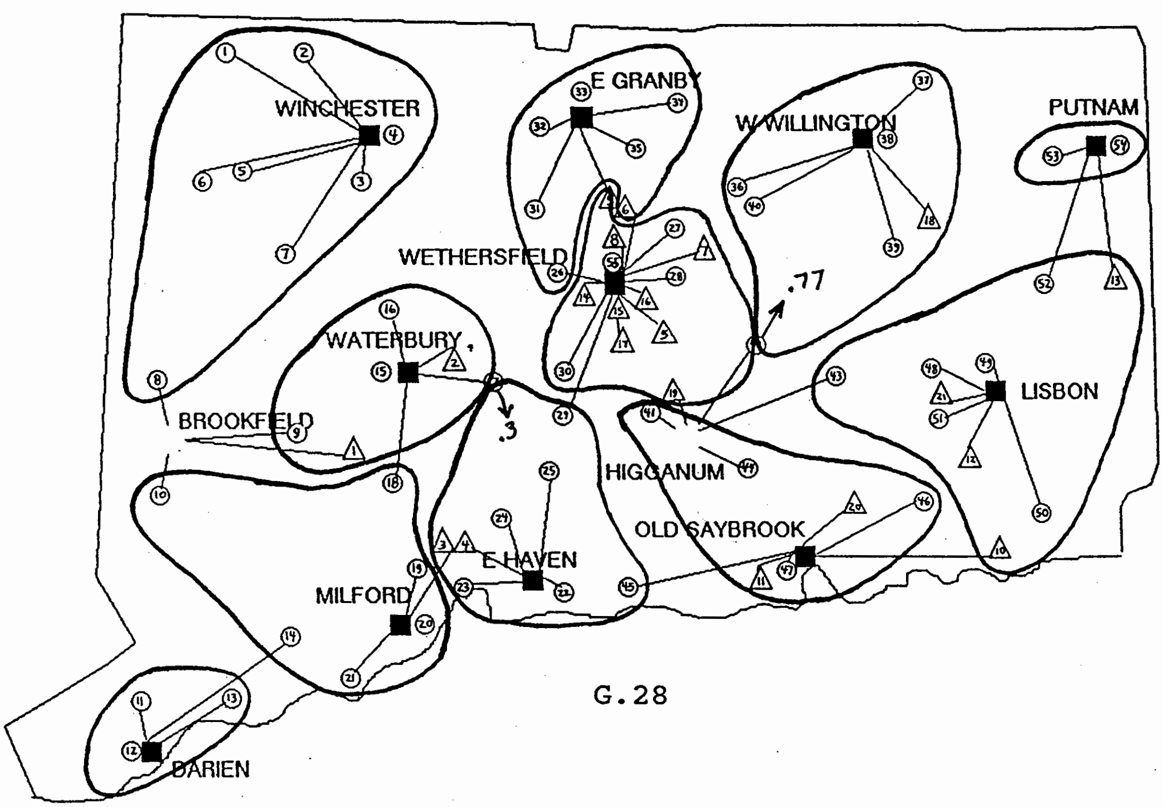
Total annualized cost
(in thousands of dollars): 3537.80

Annualized cost components relative to optimal 13-facility solution (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-510.0	+172.1		-337.9

Net present value of savings: $ 3.5 million

Savings compared to those offered by optimal, unrestricted solution: 43 %



SOLUTION SUMMARY PAGE

Run title:
Cost Sens. (T-20, O-20, unrestricted)

Scenario

Overhead costs: - 20 %   Transportation costs: - 20 %

Demand level: Normal   # of facilities: unrestricted

Solution

Facilities closed: Brookfield, East Haven, Higganum, East Granby, Putnam, Darien.

Facilities expanded:	Waterbury,	Wethersfield,	Milford
(# of bays added)	(+4.4)	(+10)	(+5.6)

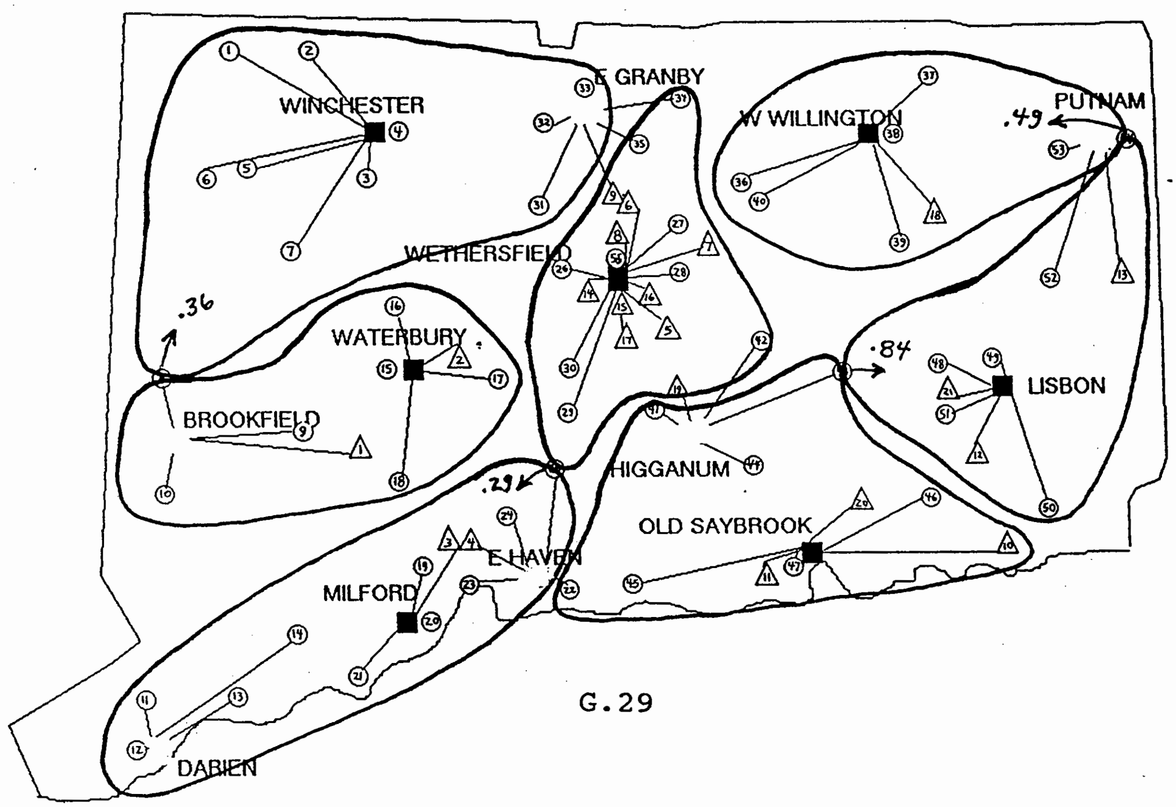
Total annualized cost
(in thousands of dollars): 2789.12

Annualized cost components relative to optimal 13-facility solution (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-1146.7	+461.2	+179.5	-506.0

Net present value of savings: $ 5.3 million

Savings compared to those offered by optimal, unrestricted solution: 100 %



SOLUTION SUMMARY PAGE

Run title:
Cost Sens. (T-20, O-20, 10)

Scenario

Overhead costs: - 20 %   Transportation costs: - 20 %

Demand level: Normal   # of facilities: 10

Solution

Facilities closed: Brookfield, East Haven, Higganum

Facilities expanded: Waterbury, Wethersfield
(# of bays added) (+3.5) (+6)

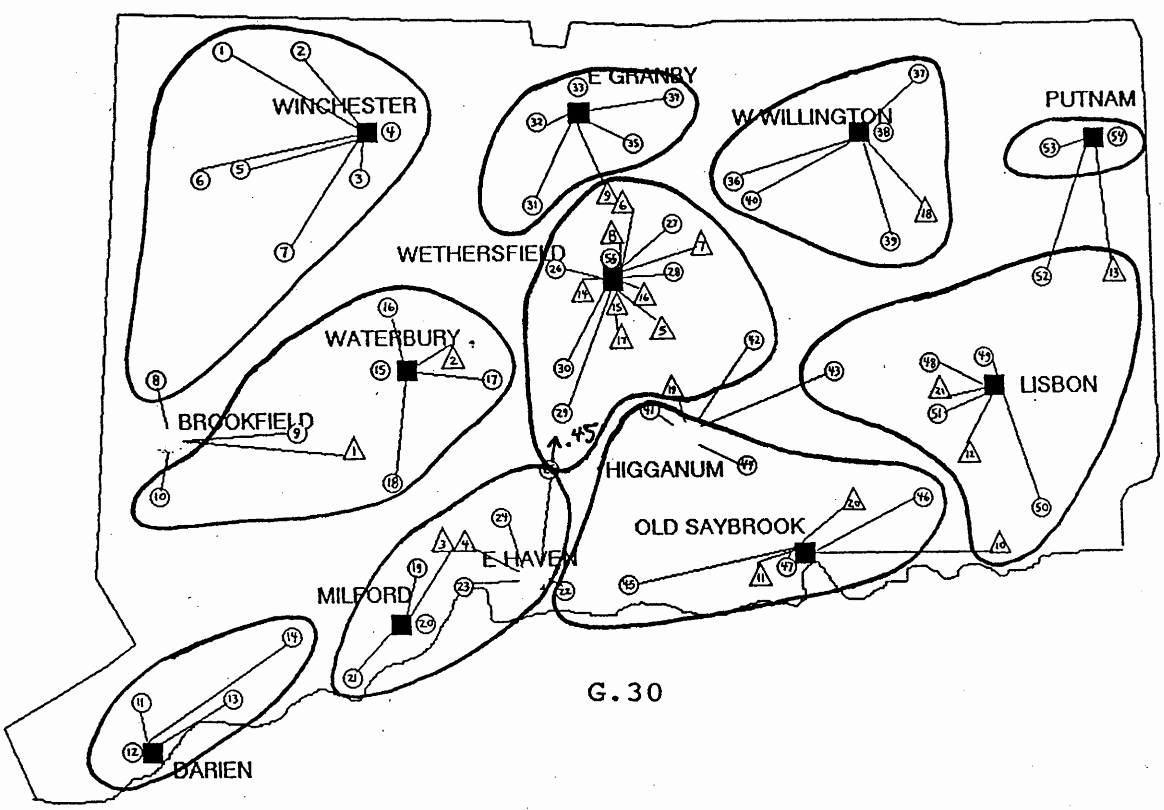
Total annualized cost
(in thousands of dollars): 2946.16

Annualized cost components relative to optimal 13-facility solution (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-636.4	+199.0	+88.5	-348.9

Net present value of savings: $ 3.7 million

Savings compared to those offered
by optimal, unrestricted solution: 69 %



SOLUTION SUMMARY PAGE

Run title:
Cost Sens. (T-20, O-20, 11)

Scenario

Overhead costs: - 20 % Transportation costs: - 20 %
Demand level: Normal # of facilities: 11
East Haven remains open, and no expansion at Wethersfield.

Solution

Facilities closed: Brookfield, Higganum

Facilities expanded: None
(# of bays added)

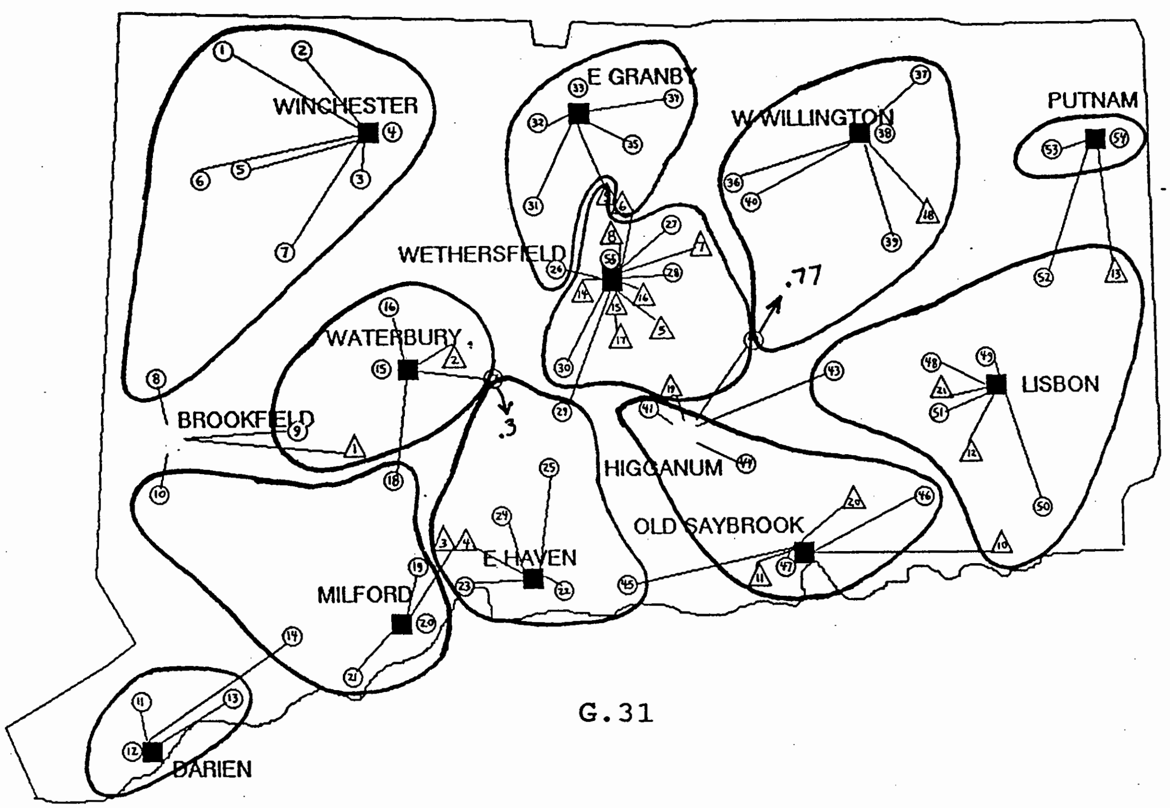
Total annualized cost
(in thousands of dollars): 3059.24

Annualized cost components relative to optimal 13-facility solution (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-408.4	+172.1		-235.9

Net present value of savings: $ 2.5 million

Savings compared to those offered
by optimal, unrestricted solution: 47 %



SOLUTION SUMMARY PAGE

Run title:
Cost Sens. (T normal, O+20, unrestricted)

Scenario

Overhead costs: + 20 %   Transportation costs: Normal

Demand level: Normal   # of facilities: unrestricted

Solution

Facilities closed: Brookfield, East Haven, Higganum, Darien, Lisbon, East Granby, West Willington

Facilities expanded: Waterbury(+5.4), Wethersfield(+10), Milford(+9.1), Old Saybrook (+5.5)
(# of bays added)

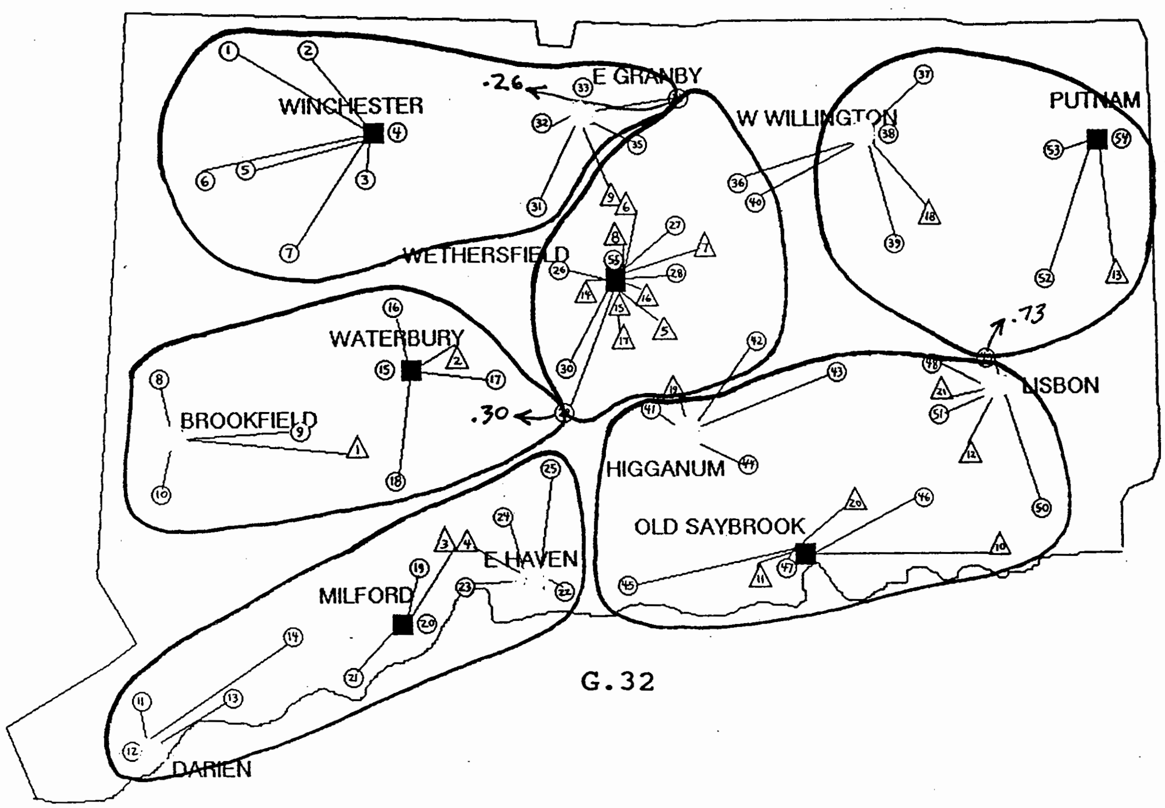
Total annualized cost
(in thousands of dollars): 3734.53

Annualized cost components relative to optimal 13-facility solution (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-2035.7	+804.3	+266.4	-965.0

Net present value of savings: $ 10.1 million

Savings compared to those offered
by optimal, unrestricted solution: 100 %



SOLUTION SUMMARY PAGE

Run title:
Cost Sens. (T normal, O+20, 10)

Scenario

Overhead costs: + 20 %

Transportation costs: Normal

Demand level: Normal

# of facilities: 10

Solution

Facilities closed: Brookfield, East Haven, Higganum

Facilities expanded: Waterbury, Wethersfield,
(# of bays added) (+3.5) (+8.6)

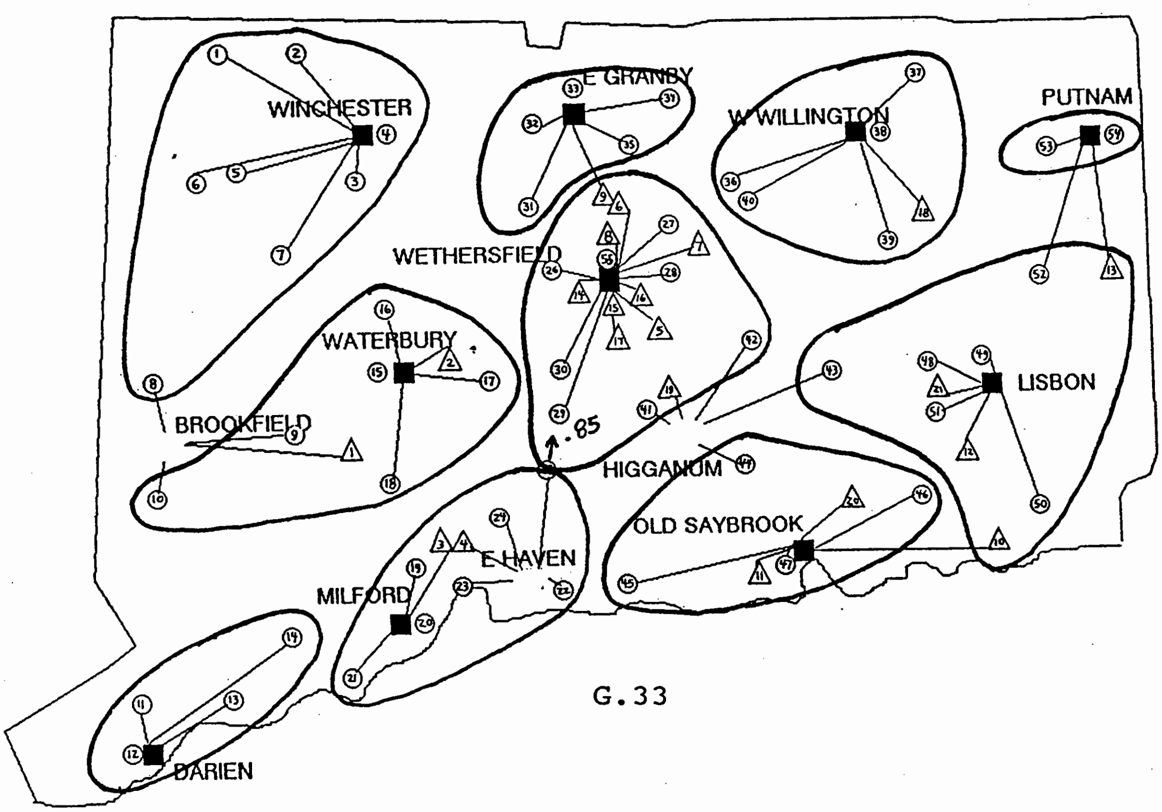
Total annualized cost
(in thousands of dollars): 4080.11

Annualized cost components relative to optimal 13-facility solution (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-954.6	+225.5	+109.7	-619.4

Net present value of savings: $ 6.5 million

Savings compared to those offered
by optimal, unrestricted solution: 64 %



SOLUTION SUMMARY PAGE

Run title:
Cost Sens. (T normal, O+20, 11)

Scenario

Overhead costs: + 20 % Transportation costs: Normal
Demand level: Normal # of facilities: 11
East Haven remains open, and no expansion at Wethersfield.

Solution

Facilities closed: Brookfield, Higganum

Facilities expanded: None
(# of bays added)

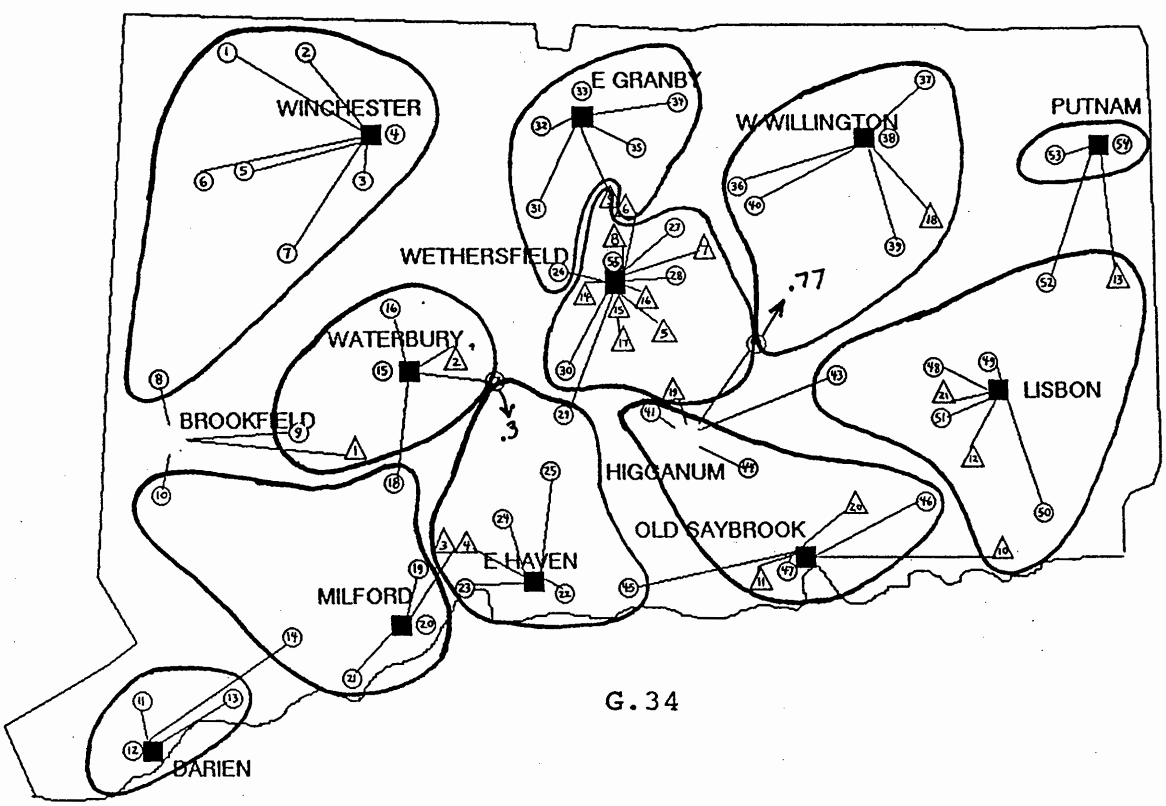
Total annualized cost
(in thousands of dollars): 4302.61

Annualized cost components relative to optimal 13-facility solution (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-612.0	+215.1		-396.9

Net present value of savings: $ 4.2 million

Savings compared to those offered by optimal, unrestricted solution: 41 %



SOLUTION SUMMARY PAGE

Run title:
Cost Sens. (T normal, 0-20, unrestricted)

<u>Scenario</u>

Overhead costs: - 20 %

Transportation costs: Normal

Demand level: Normal

# of facilities: unrestricted

<u>Solution</u>

Facilities closed: Brookfield, East Haven, Higganum, East Granby, Putnam

Facilities expanded: Waterbury, Wethersfield
(# of bays added) (+4.4) (+10)

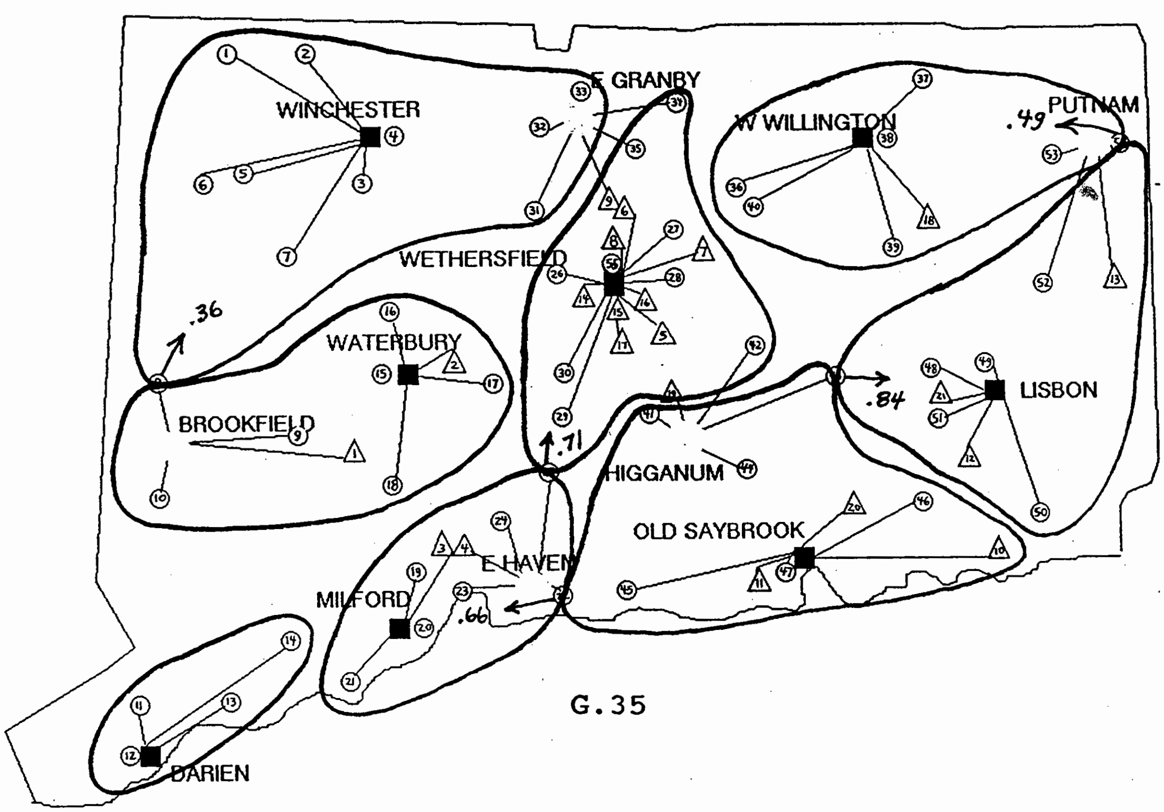
Total annualized cost
(in thousands of dollars): 3133.84

Annualized cost components relative to optimal 13-facility solution (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-957.5	+424.7	+128.3	-404.5

Net present value of savings: $ 4.2 million

Savings compared to those offered
by optimal, unrestricted solution: 100 %



SOLUTION SUMMARY PAGE

Run title:
Cost Sens. (T normal, 0-20, 10)

Scenario

Overhead costs: - 20 % Transportation costs: Normal

Demand level: Normal # of facilities: 10

Solution

Facilities closed: Brookfield, East Haven, Higganum

Facilities expanded: Waterbury, Wethersfield
(# of bays added) (+3.5) (+8.6)

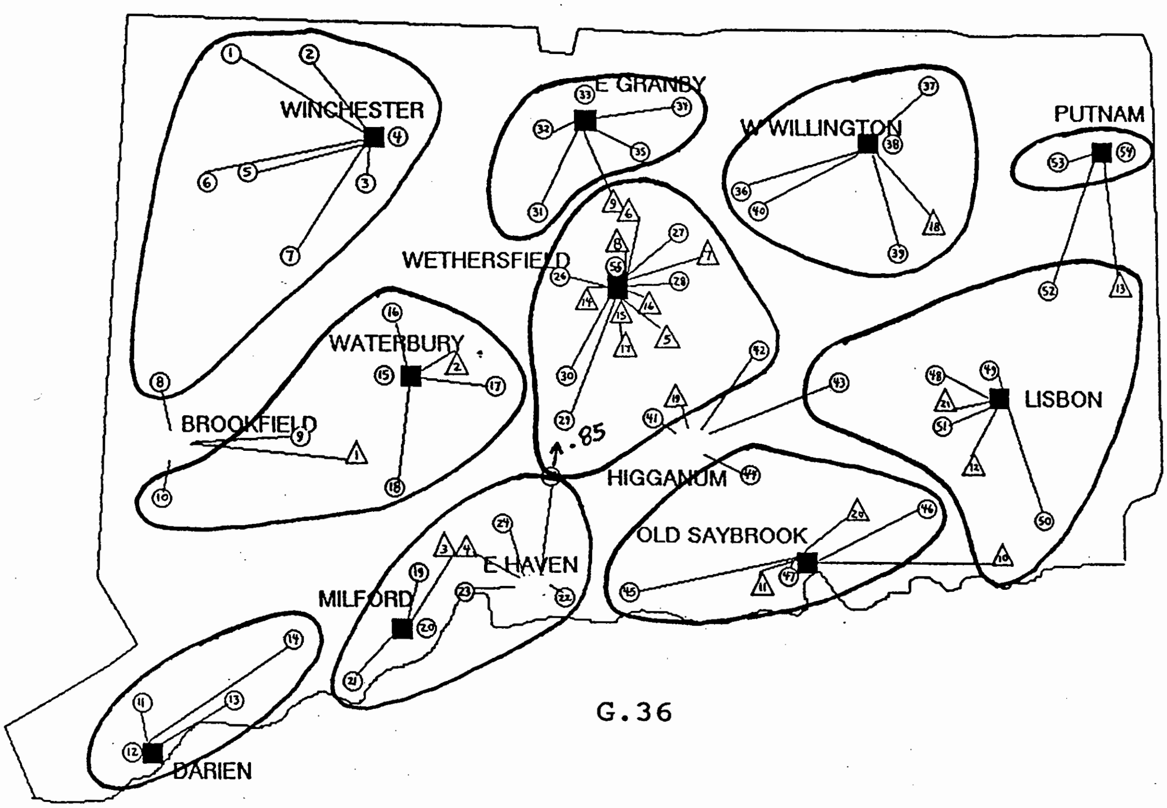
Total annualized cost
(in thousands of dollars): 3237.19

Annualized cost components relative to optimal 13-facility solution (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-636.4	+225.6	+109.7	-301.1

Net present value of savings: $ 3.2 million

Savings compared to those offered
by optimal, unrestricted solution: 75 %



SOLUTION SUMMARY PAGE

Run title:
Cost Sens. (T normal, 0-20, 11)

Scenario

Overhead costs: - 20 %　　Transportation costs: Normal
Demand level: Normal　　# of facilities: 11
East Haven remains open, and no expansion at Wethersfield.

Solution

Facilities closed: Brookfield, Higganum

Facilities expanded: None
(# of bays added)

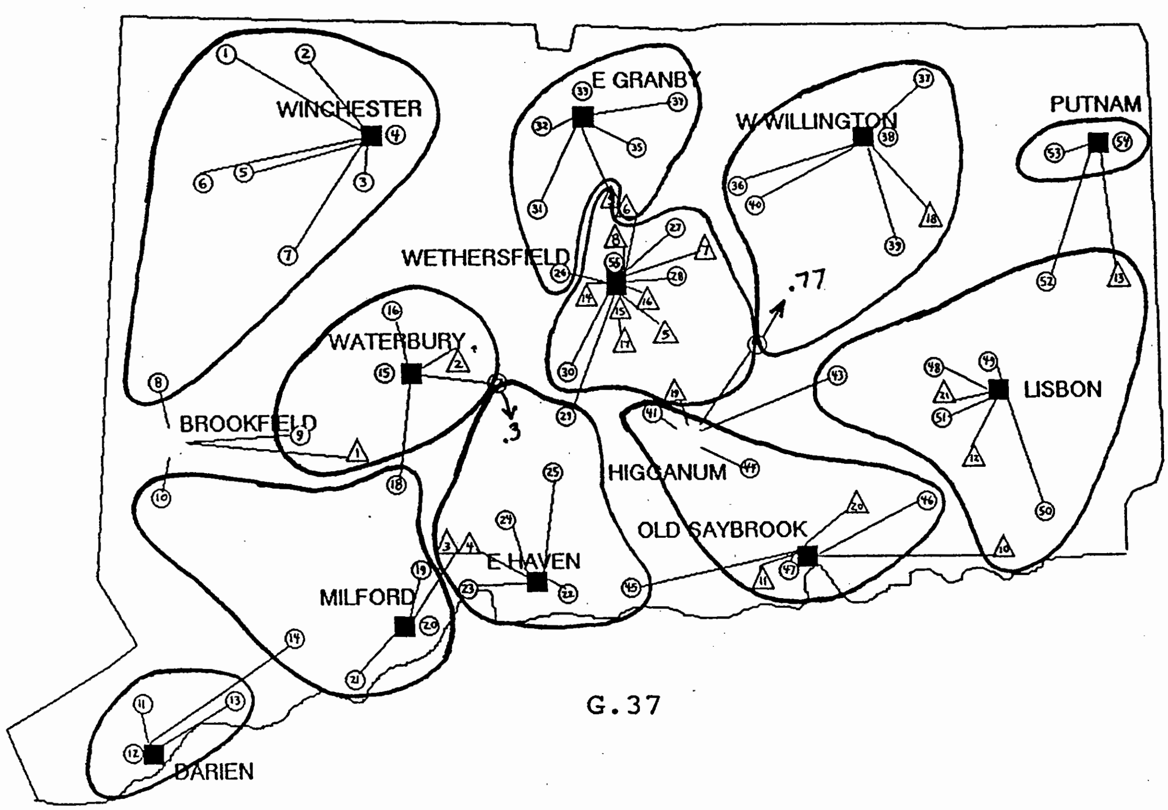
Total annualized cost
(in thousands of dollars): 3345.49

Annualized cost components relative to optimal 13-facility solution (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-408.0	+215.2		-192.8

Net present value of savings: $ 2.0 million

Savings compared to those offered by optimal, unrestricted solution: 48 %



SOLUTION SUMMARY PAGE

Run title: Cost Sens. (T+20, O+20, unrestricted)

Scenario

Overhead costs: + 20 % Transportation costs: + 20 %

Demand level: Normal # of facilities: unrestricted

Solution

Facilities closed: Brookfield, East Haven, Higganum, East Granby, Putnam, Darien

Facilities expanded:	Waterbury,	Wethersfield,	Milford
(# of bays added)	(+4.9)	(+10)	(+6.9)

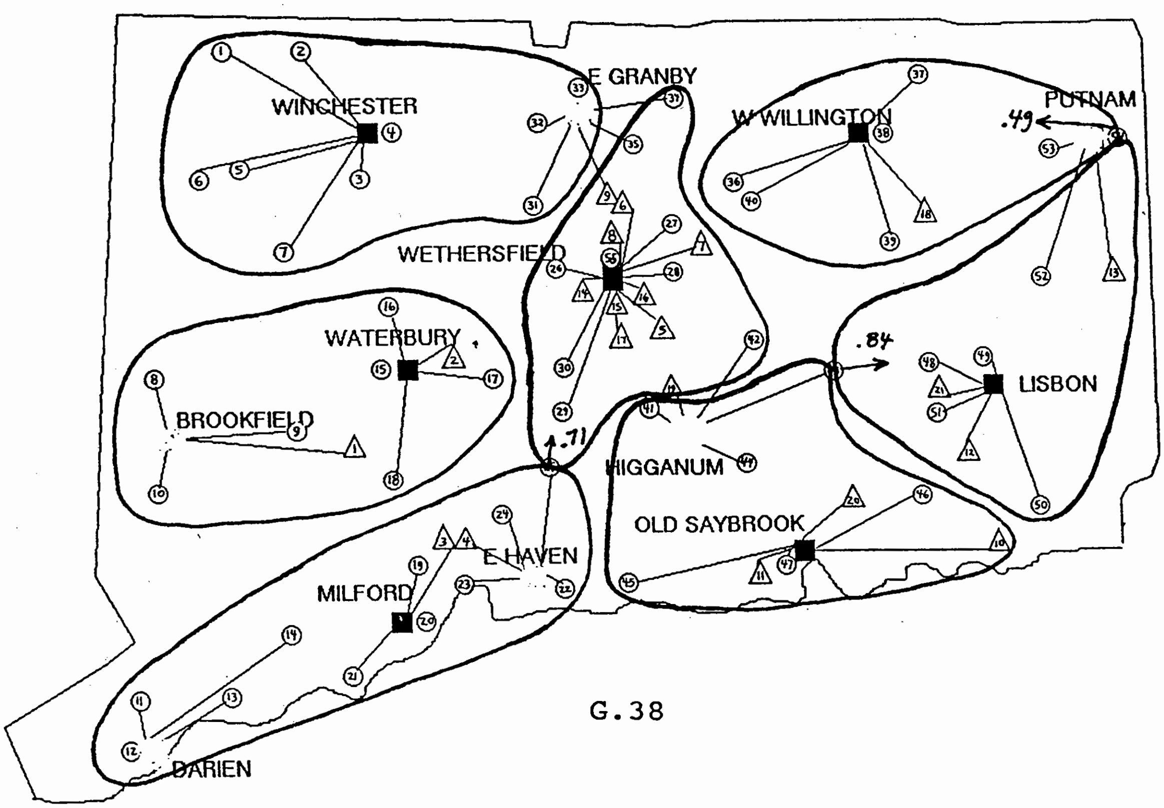
Total annualized cost (in thousands of dollars): 4092.05

Annualized cost components relative to optimal 13-facility solution (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-1720.1	+675.6	+193.8	-850.7

Net present value of savings: $ 8.9 million

Savings compared to those offered by optimal, unrestricted solution: 100 %



SOLUTION SUMMARY PAGE

Run title:
Cost Sens. (T+20, O+20, 10)

Scenario

Overhead costs: + 20 % Transportation costs: + 20 %

Demand level: Normal # of facilities: 10

Solution

Facilities closed: Brookfield, East Haven, Higganum

Facilities expanded: Waterbury, Wethersfield
(# of bays added) (+4.9) (+8.6)

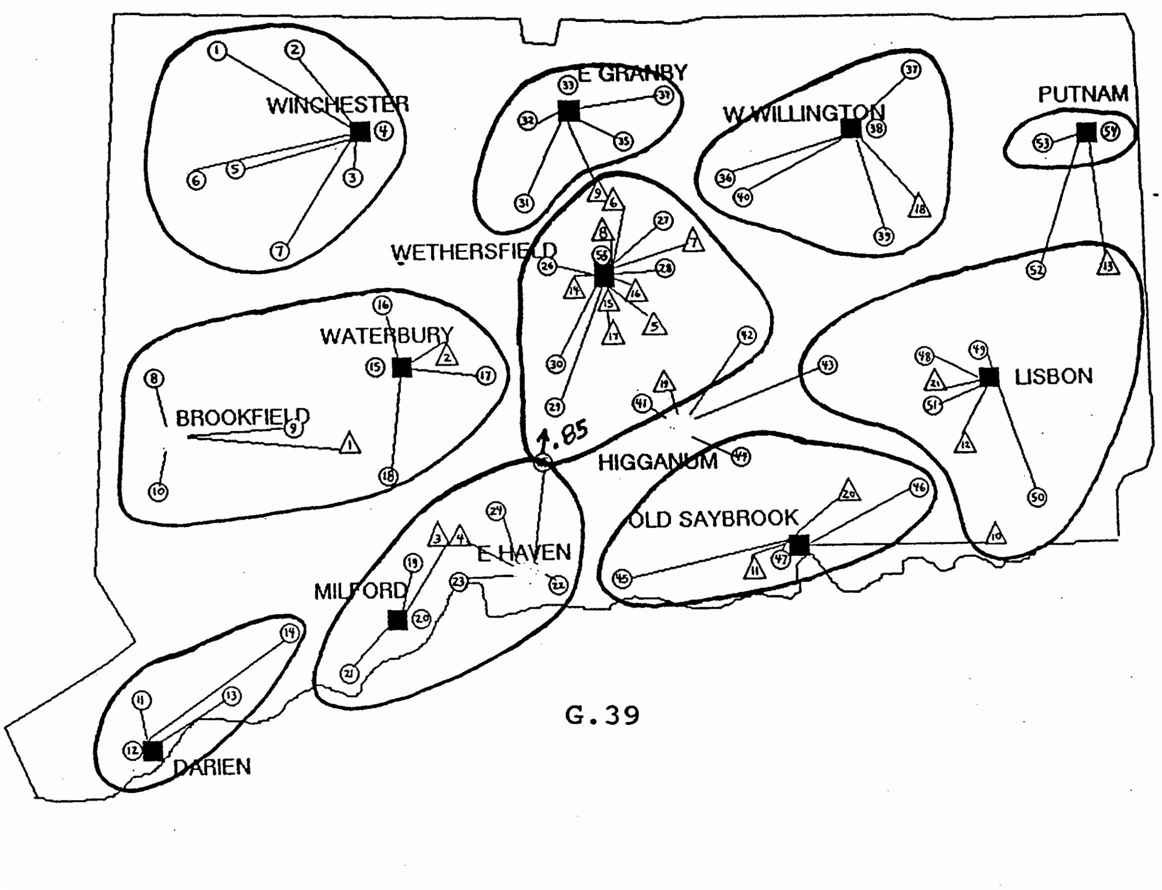
Total annualized cost
(in thousands of dollars): 4366.93

Annualized cost components relative to optimal 13-facility solution (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-954.6	+257.8	+121.0	-575.8

Net present value of savings: $ 6.0 million

Savings compared to those offered by optimal, unrestricted solution: 68 %



SOLUTION SUMMARY PAGE

Run title:
Cost Sens. (T+20, O+20, 11)

Scenario

Overhead costs: + 20 % Transportation costs: + 20 %
Demand level: Normal # of facilities: 11
East Haven remains open, and no expansion at Wethersfield.

Solution

Facilities closed: Brookfield, Higganum

Facilities expanded: None
(# of bays added)

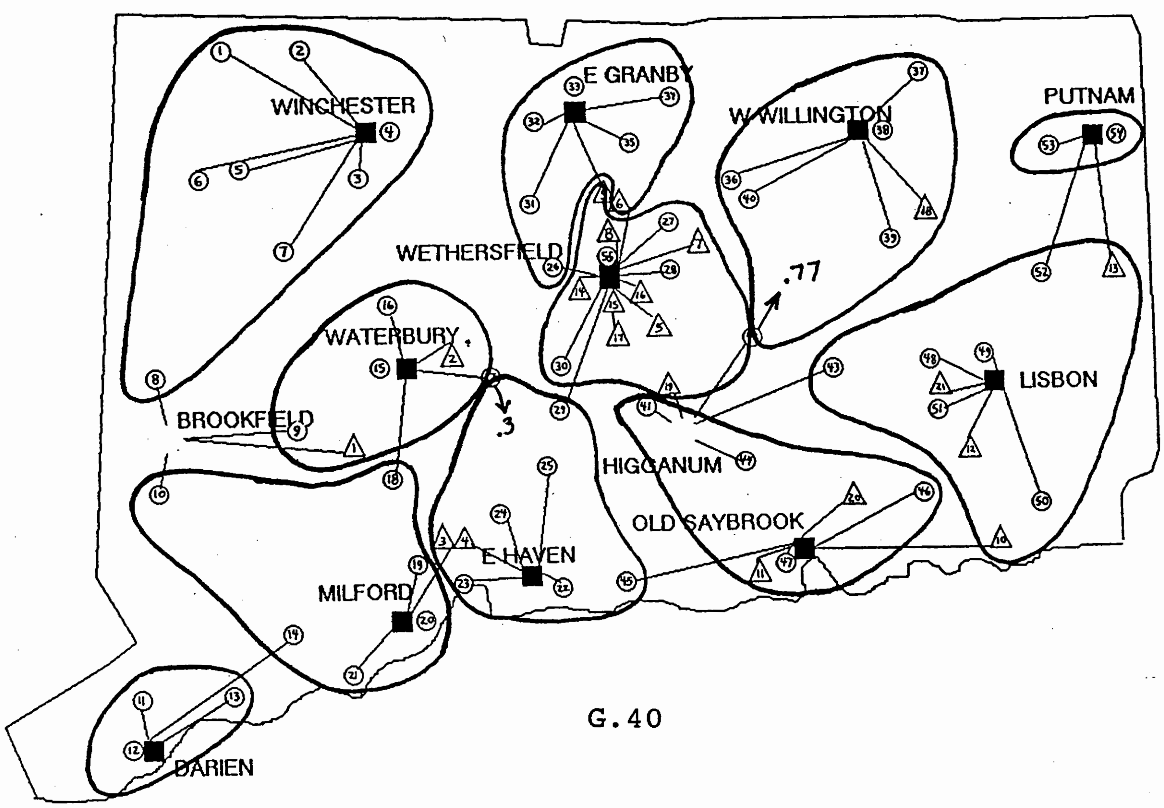
Total annualized cost
(in thousands of dollars): 4588.86

Annualized cost components relative to optimal 13-facility solution (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-612.0	+258.2		-353.8

Net present value of savings: $ 3.7 million

Savings compared to those offered by optimal, unrestricted solution: 42 %



SOLUTION SUMMARY PAGE

Run title: Cost Sens. (T+20, O normal, unrestricted)

Scenario

Overhead costs: Normal

Transportation costs: + 20 %

Demand level: Normal

# of facilities: unrestricted

Solution

Facilities closed: Brookfield, East Haven, Higganum, East Granby, Putnam, Darien

Facilities expanded:	Waterbury,	Wethersfield,	Milford
(# of bays added)	(+4.9)	(+10)	(+6.9)

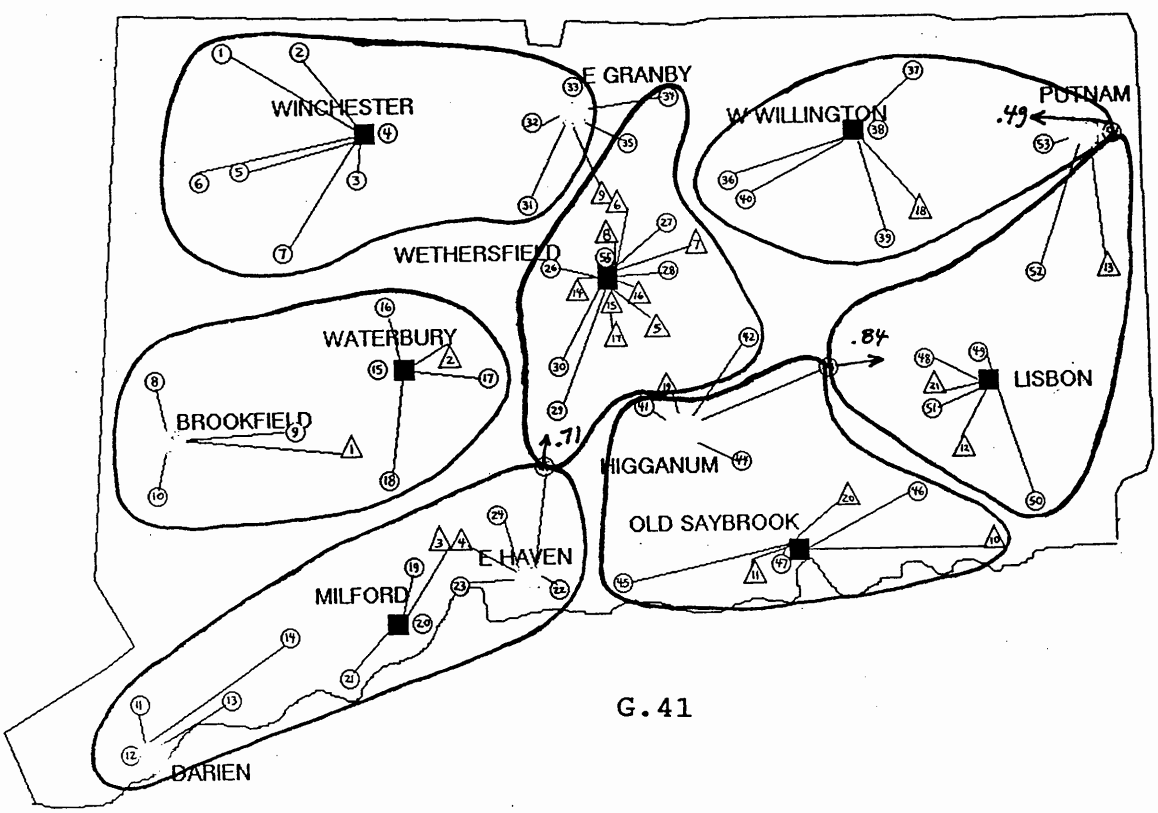
Total annualized cost
(in thousands of dollars): 3798.17

Annualized cost components relative to optimal 13-facility solution (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-1433.4	+675.7	+193.8	-563.9

Net present value of savings: $ 5.9 million

Savings compared to those offered
by optimal, unrestricted solution: 100 %



SOLUTION SUMMARY PAGE

Run title:
Cost Sens. (T+20, O normal, 10)

<u>Scenario</u>

Overhead costs: Normal   Transportation costs: + 20 %

Demand level: Normal   # of facilities: 10

<u>Solution</u>

Facilities closed: Brookfield, East Haven, Higganum

Facilities expanded: Waterbury, Wethersfield
(# of bays added) (+4.9) (+8.6)

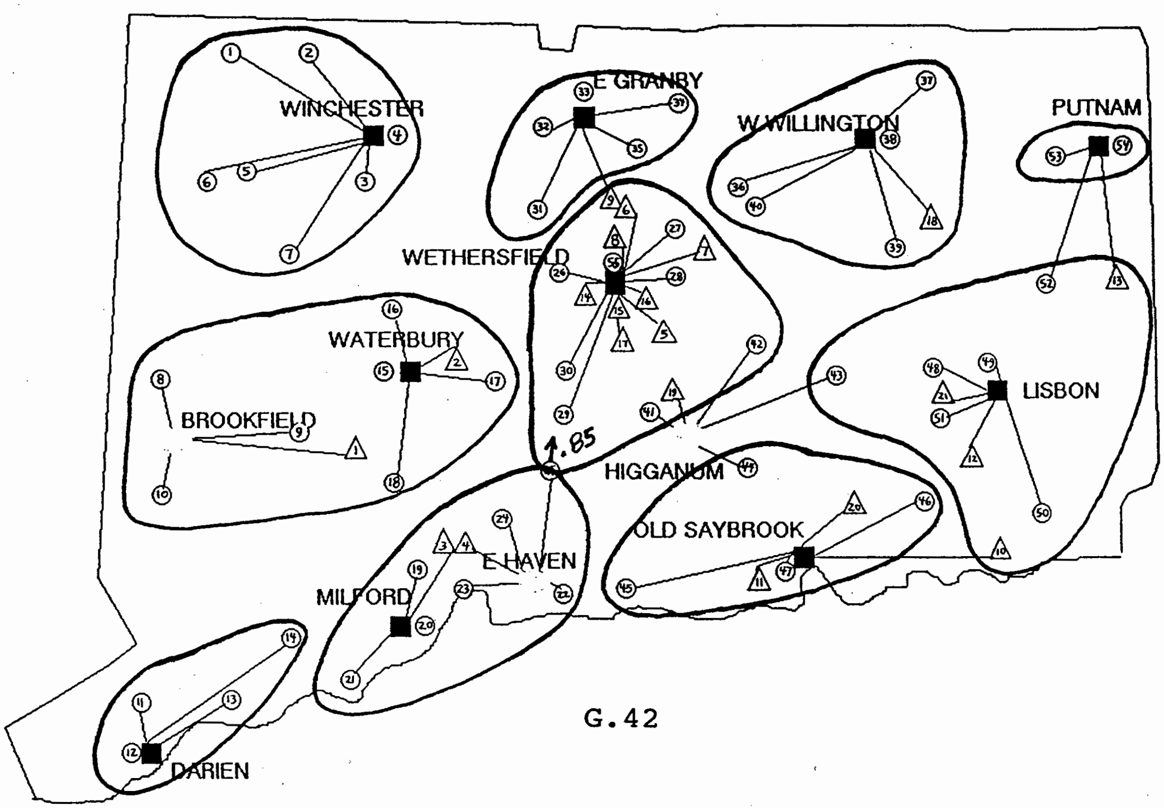
Total annualized cost
(in thousands of dollars): 3945.47

Annualized cost components relative to optimal 13-facility solution (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-795.5	+257.9	+121.0	-416.6

Net present value of savings: $ 4.4 million

Savings compared to those offered
by optimal, unrestricted solution: 74 %



SOLUTION SUMMARY PAGE

Run title:
Cost Sens. (T+20, 0 normal, 11)

Scenario

Overhead costs: Normal   Transportation costs: + 20 %
Demand level: Normal   # of facilities: 11
East Haven remains open, and no expansion at Wethersfield.

Solution

Facilities closed: Brookfield, Higganum

Facilities expanded: None
(# of bays added)

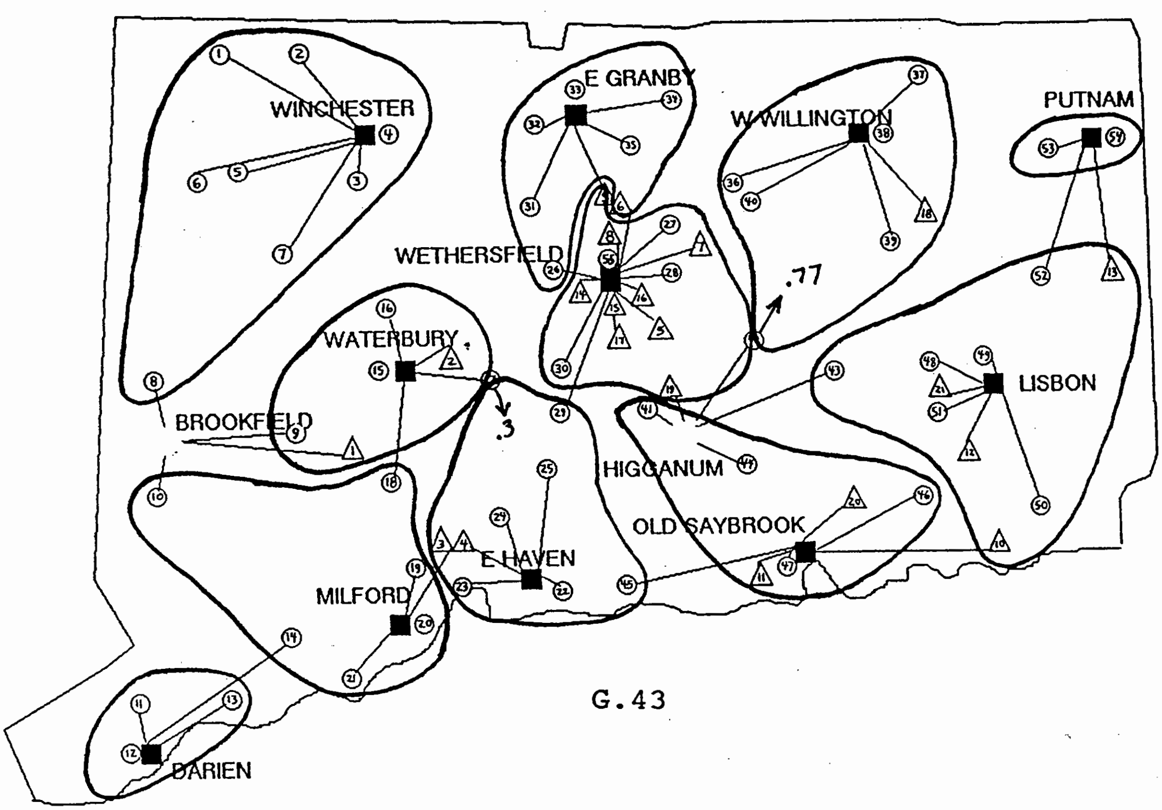
Total annualized cost
(in thousands of dollars): 4110.30

Annualized cost components relative to optimal 13-facility solution (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-510.0	+258.2		-251.8

Net present value of savings: $ 2.6 million

Savings compared to those offered
by optimal, unrestricted solution: 45 %



SOLUTION SUMMARY PAGE

Run title:
Cost Sens. (T+20, O-20, unrestricted)

<u>Scenario</u>

Overhead costs: - 20 %   Transportation costs: + 20 %

Demand level: Normal   # of facilities: unrestricted

<u>Solution</u>

Facilities closed: Brookfield, East Haven, Higganum,
East Granby, Putnam

Facilities expanded: Waterbury, Wethersfield
(# of bays added) (+4.9) (+10)

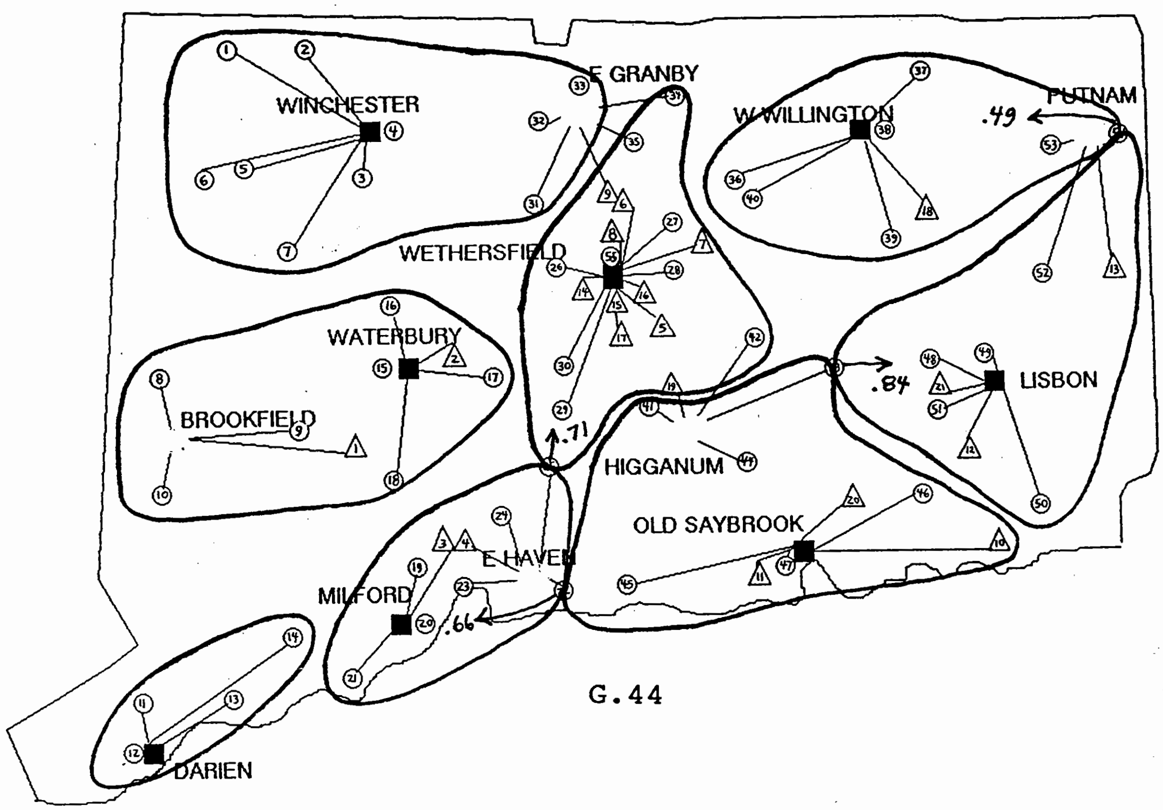
Total annualized cost
(in thousands of dollars): 3461.45

Annualized cost components relative to optimal 13-facility solution (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-957.5	+505.2	+132.3	-320.0

Net present value of savings: $ 3.4 million

Savings compared to those offered
by optimal, unrestricted solution: 100 %



SOLUTION SUMMARY PAGE

Run title: Cost Sens. (T+20, O-20, 10)

Scenario

Overhead costs: - 20 % Transportation costs: + 20 %

Demand level: Normal # of facilities: 10

Solution

Facilities closed: Brookfield, East Haven, Higganum

Facilities expanded: Waterbury, Wethersfield
(# of bays added) (+4.9) (+8.6)

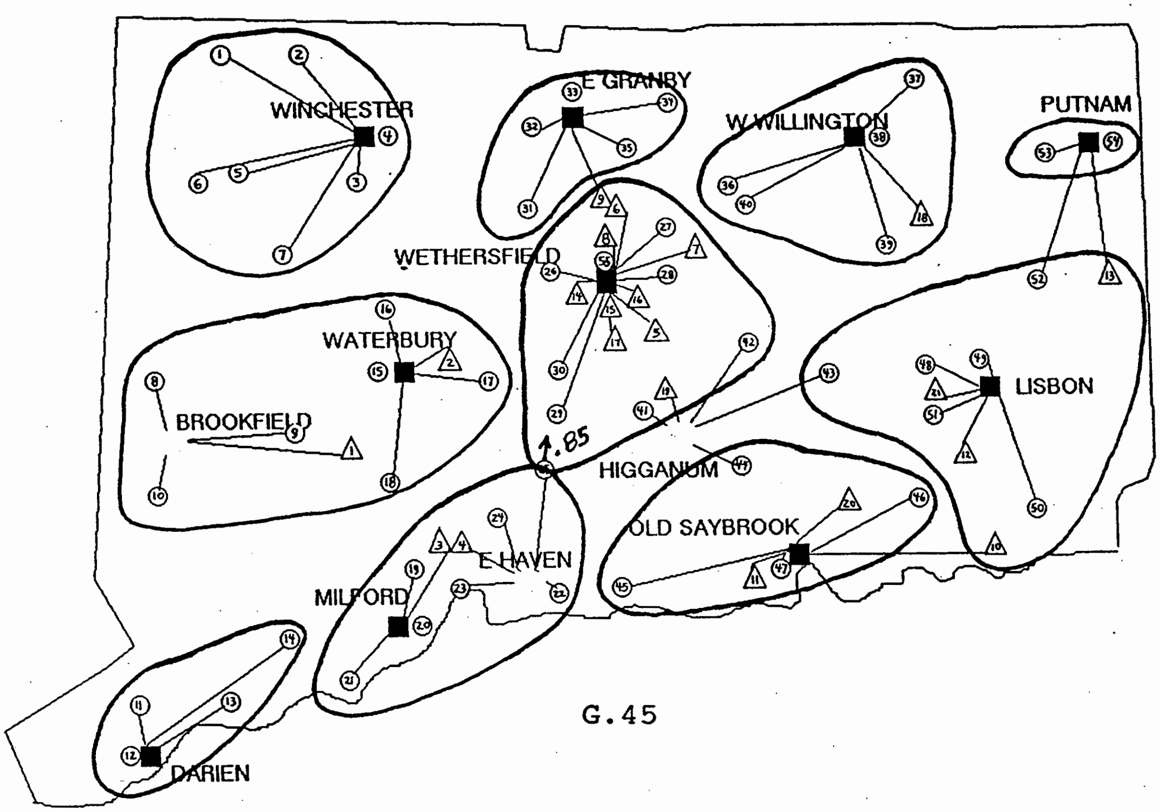
Total annualized cost
(in thousands of dollars): 3524.01

Annualized cost components relative to optimal 13-facility solution (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-636.4	+257.9	+121.0	-257.5

Net present value of savings: $ 2.7 million

Savings compared to those offered
by optimal, unrestricted solution: 80 %



SOLUTION SUMMARY PAGE

Run title:
Cost Sens. (T+20, O-20, 11)

Scenario

Overhead costs: - 20 % Transportation costs: + 20 %
Demand level: Normal # of facilities: 11
East Haven remains open, and no expansion at Wethersfield.

Solution

Facilities closed: Brookfield, Higganum

Facilities expanded: None
(# of bays added)

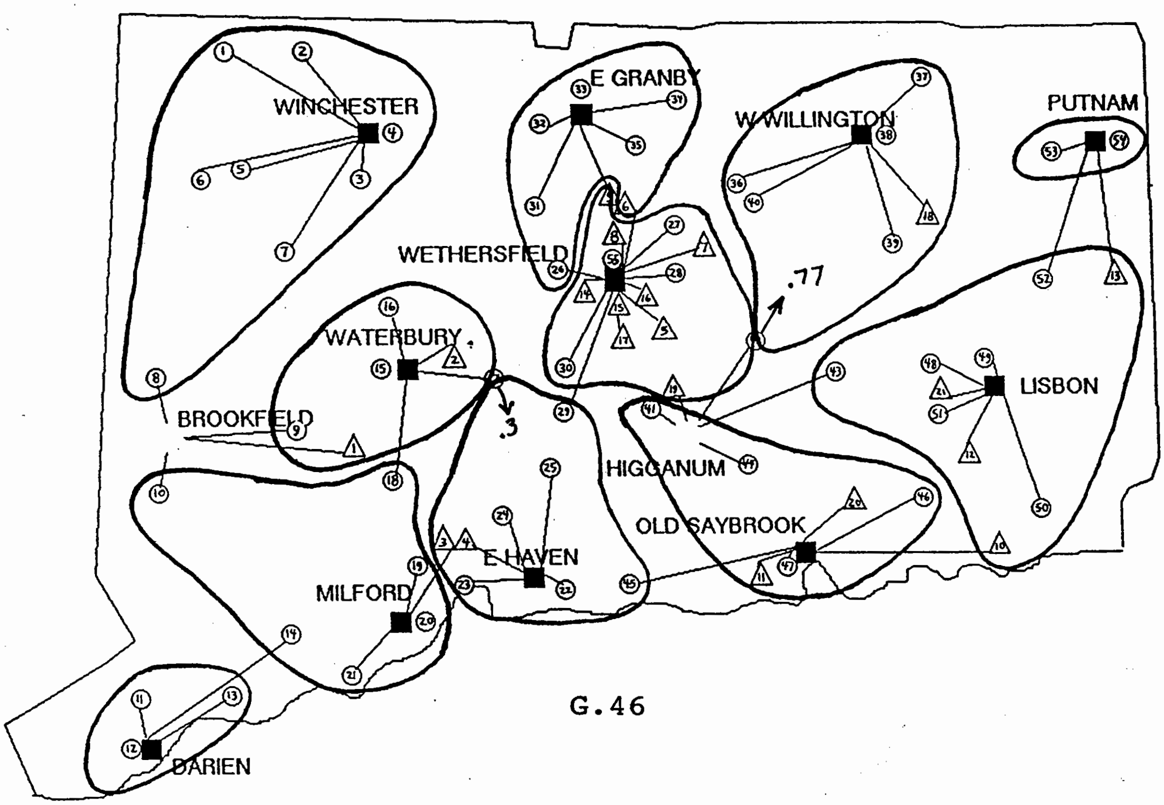
Total annualized cost
(in thousands of dollars): 3631.74

Annualized cost components relative to optimal 13-facility solution (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-408.0	+258.2		-149.8

Net present value of savings: $ 1.6 million

Savings compared to those offered by optimal, unrestricted solution: 47 %



SOLUTION SUMMARY PAGE

Run title:
Demand Sens. (D-20, unrestricted)

Scenario

Overhead costs: Normal — Transportation costs: - 20 %

Demand level: - 20 % — # of facilities: unrestricted

Solution

Facilities closed: Brookfield, East Haven, Higganum, Lisbon
East Granby, Darien, West Willington, Waterbury

Facilities expanded: Milford, Wethersfield
(# of bays added) (+8.4) (+10)

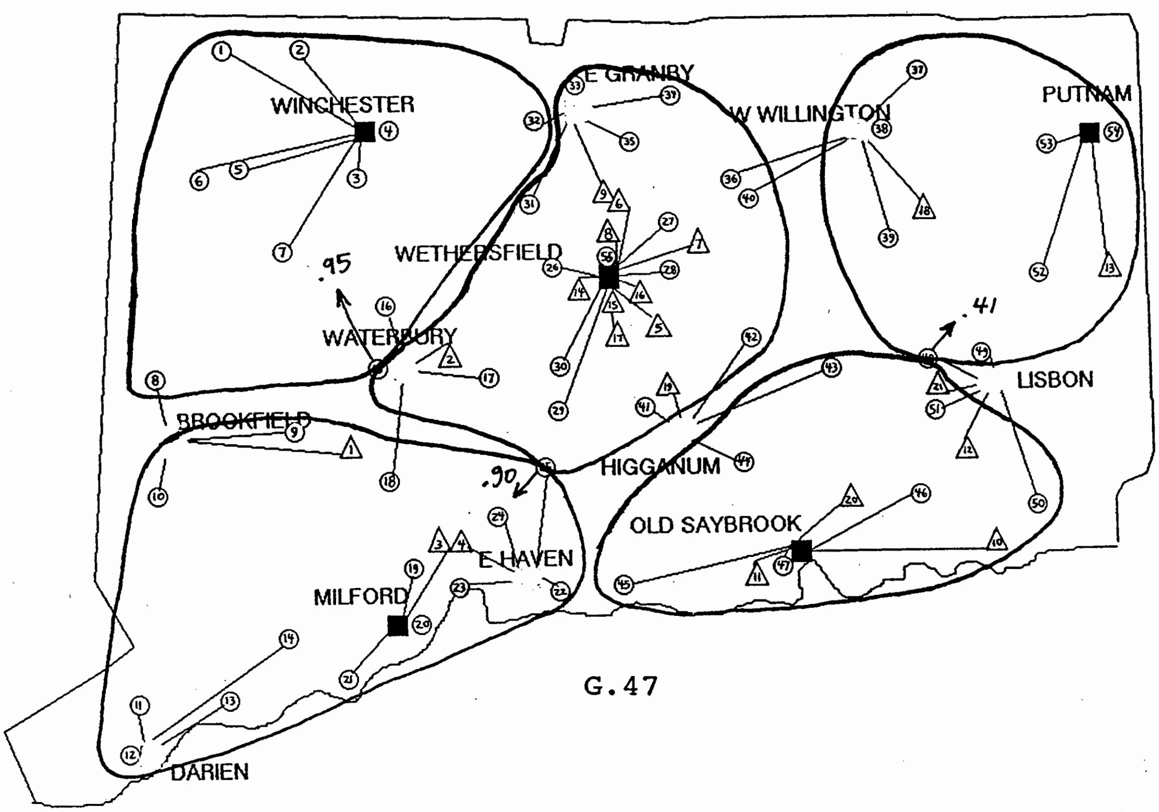
Total annualized cost
(in thousands of dollars): 2918.00

Annualized cost components relative to optimal 13-facility solution (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-1899.0	+795.1	+168.6	-935.3

Net present value of savings: $ 9.8 million

Savings compared to those offered
by optimal, unrestricted solution: 100 %



SOLUTION SUMMARY PAGE

Run title:
Demand Sens. (D-20, 10)

Scenario

Overhead costs: Normal   Transportation costs: - 20 %

Demand level: - 20 %   # of facilities: 10

Solution

Facilities closed: Brookfield, East Haven, Higganum

Facilities expanded: None
(# of bays added)

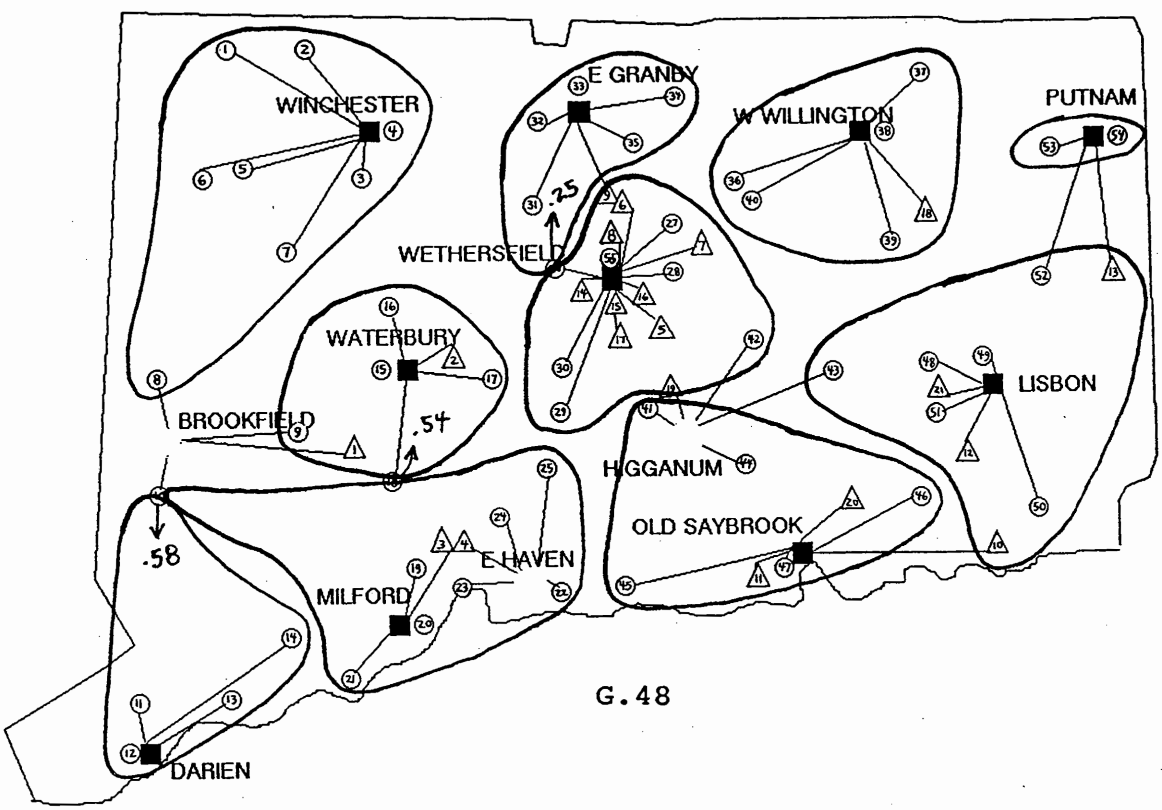
Total annualized cost
(in thousands of dollars): 3288.39

Annualized cost components relative to optimal 13-facility solution (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-795.5	+230.6		-564.9

Net present value of savings: $ 5.9 million

Savings compared to those offered
by optimal, unrestricted solution: 60 %



SOLUTION SUMMARY PAGE

Run title:
Demand Sens. (D-20, 11)

Scenario

Overhead costs: Normal Transportation costs: - 20 %
Demand level: - 20 % # of facilities: 11
East Haven remains open, and no expansion at Wethersfield.

Solution

Facilities closed: Brookfield, Higganum

Facilities expanded: None
(# of bays added)

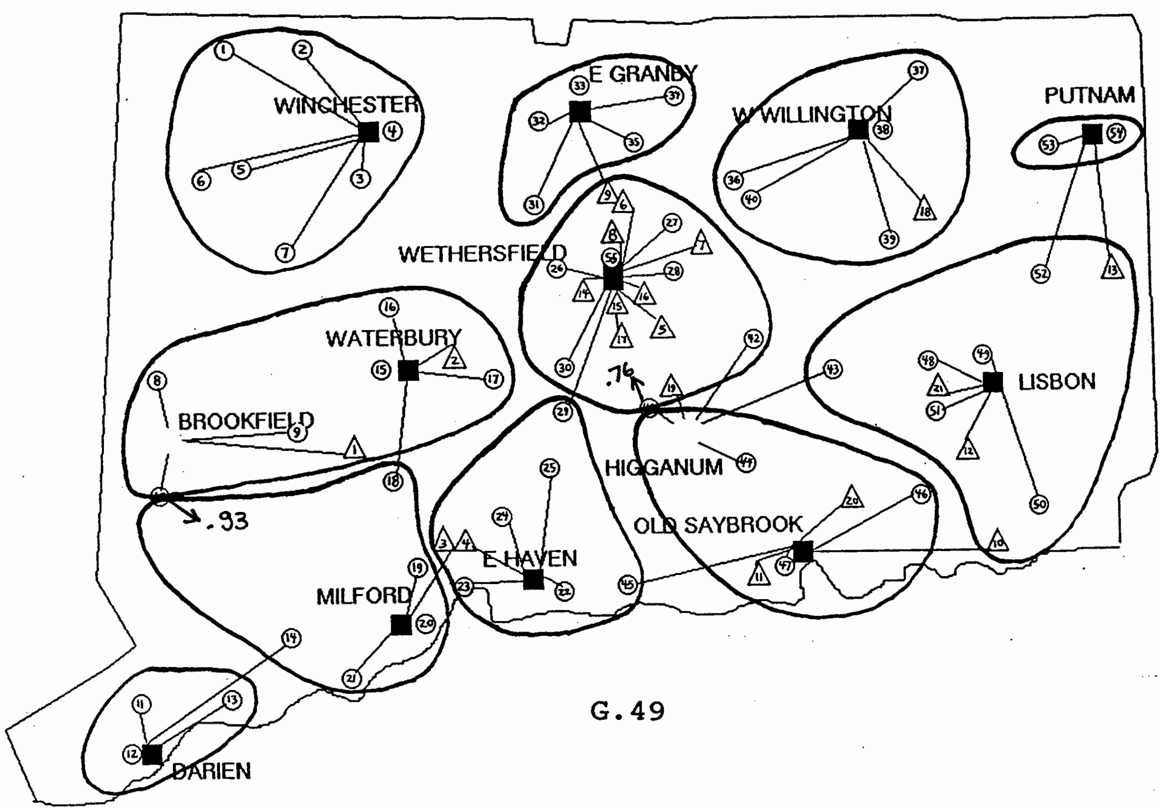
Total annualized cost
(in thousands of dollars): 3488.89

Annualized cost components relative to optimal 13-facility solution (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-510.0	+145.6		-364.4

Net present value of savings: $ 3.8 million

Savings compared to those offered
by optimal, unrestricted solution: 39 %



SOLUTION SUMMARY PAGE

Run title:
Demand Sens. (D-20, 13)

Scenario

Overhead costs: Normal

Transportation costs: - 20 %

Demand level: - 20 %

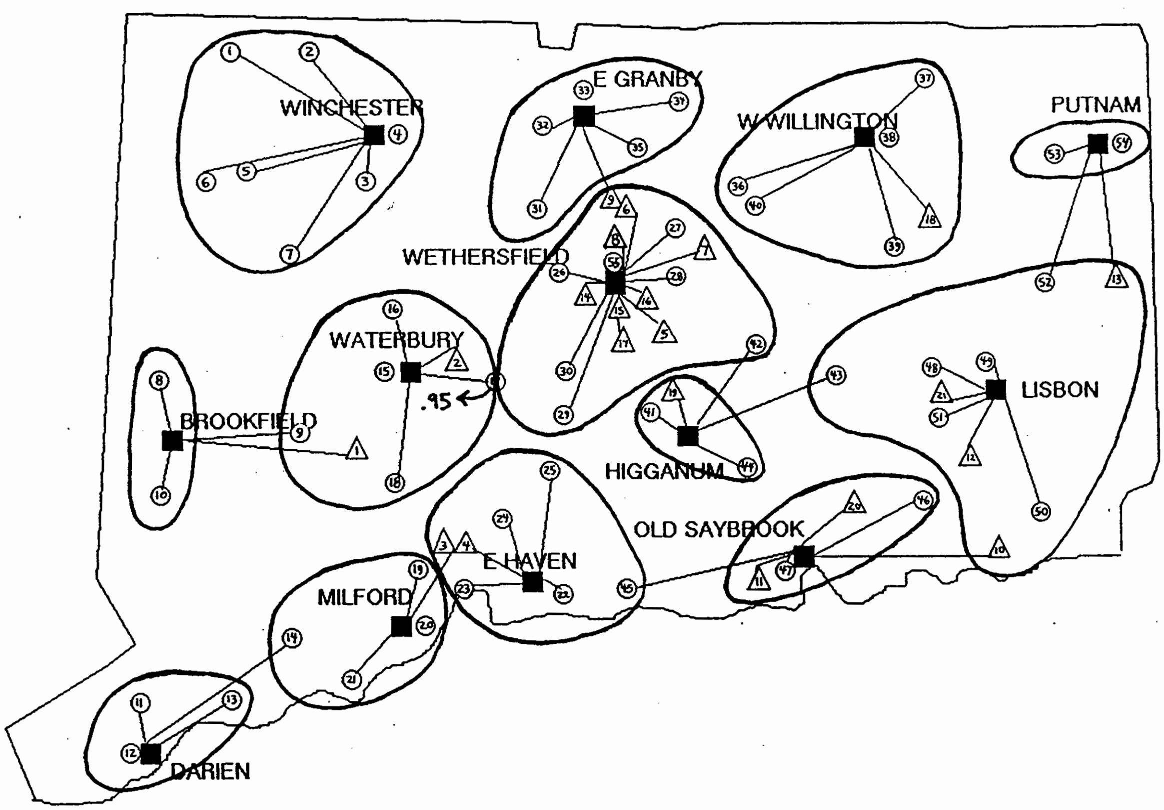
# of facilities: 13

Solution

Facilities closed: None

Facilities expanded: None
(# of bays added)

Total annualized cost
(in thousands of dollars): 3853.34



SOLUTION SUMMARY PAGE

Run title: Demand Sens. (D-10, unrestricted)

Scenario

Overhead costs: Normal

Transportation costs: - 10 %

Demand level: - 10 %

# of facilities: unrestricted

Solution

Facilities closed: Brookfield, East Haven, Higganum, Lisbon East Granby, Darien, West Willington

Facilities expanded: Milford, Wethersfield, Waterbury
(# of bays added) (+6.9) (+10) (+2.9)

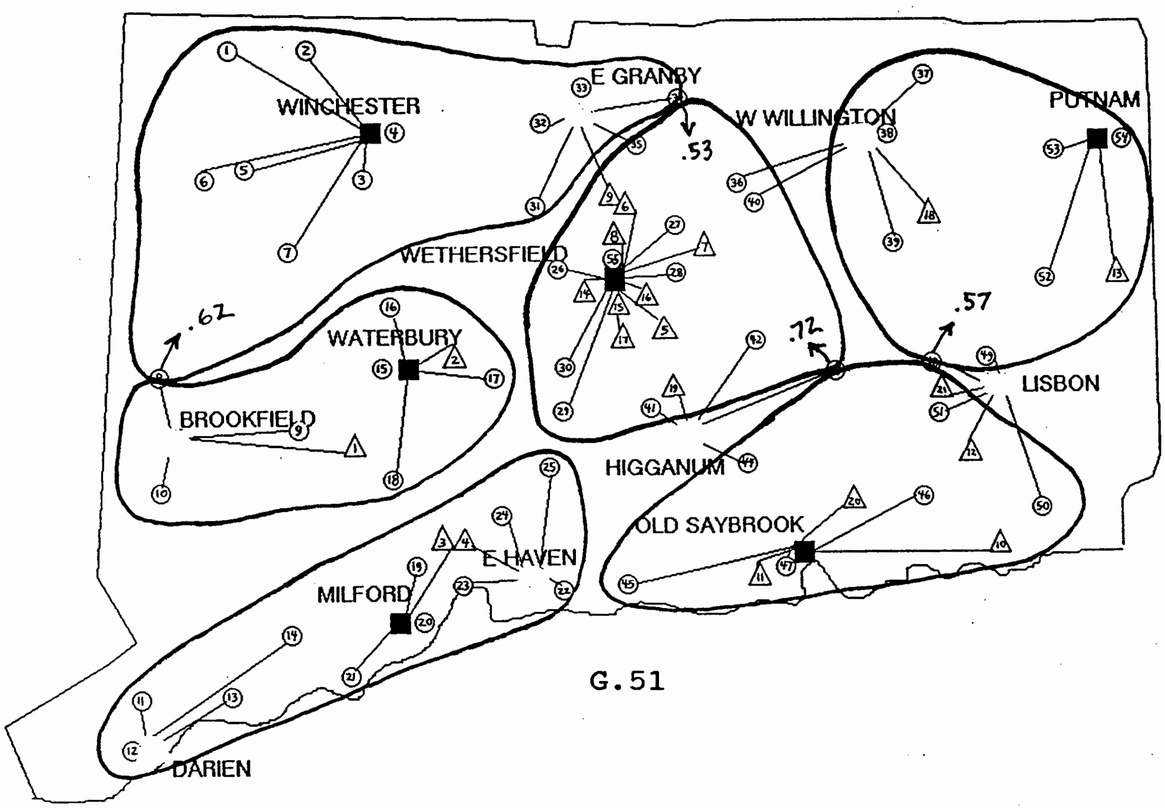
Total annualized cost (in thousands of dollars): 3197.33

Annualized cost components relative to optimal 13-facility solution (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-1696.4	+733.6	+177.9	-784.9

Net present value of savings: $ 8.2 million

Savings compared to those offered by optimal, unrestricted solution: 100 %



SOLUTION SUMMARY PAGE

Run title:
Demand Sens. (D-10, 10)

Scenario

Overhead costs: Normal   Transportation costs: - 10 %

Demand level: - 10 %   # of facilities: 10

Solution

Facilities closed: Brookfield, East Haven, Higganum

Facilities expanded: Waterbury, Wethersfield
(# of bays added) (+2.4) (+4.7)

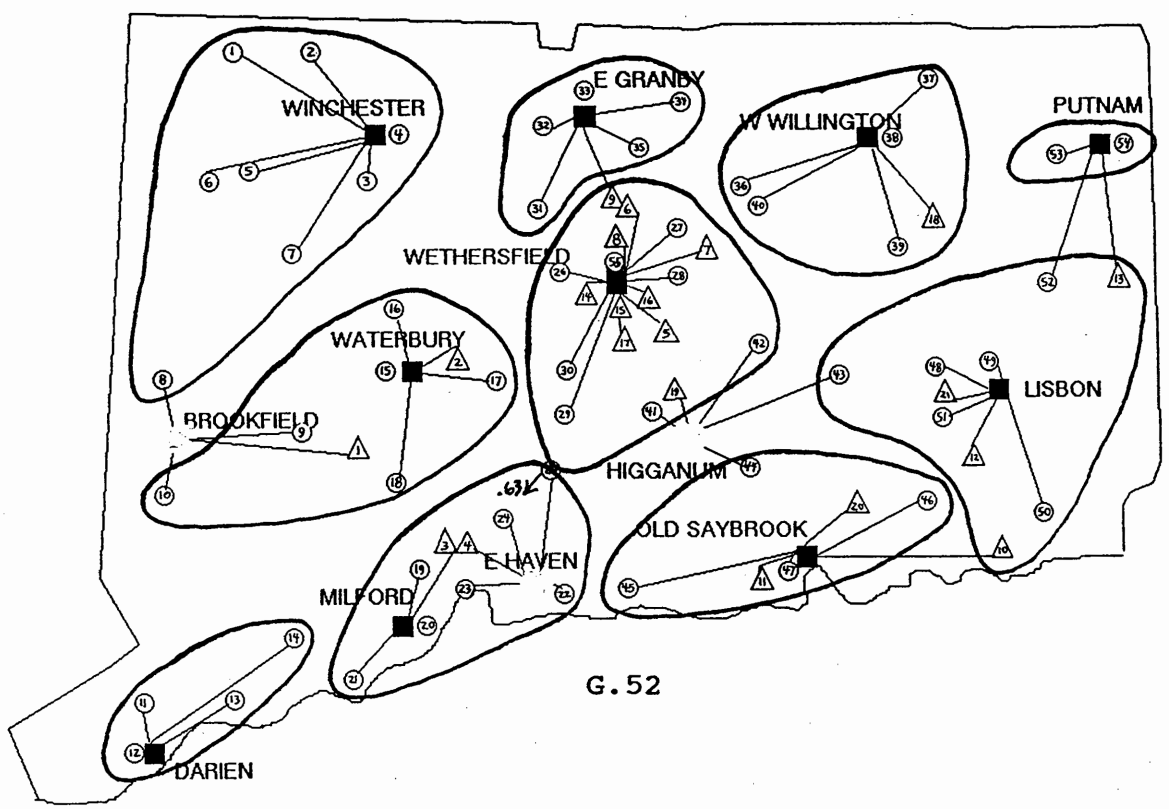
Total annualized cost
(in thousands of dollars): 3476.75

Annualized cost components relative to optimal 13-facility solution (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-795.5	+220.8	+69.3	-505.4

Net present value of savings: $ 5.3 million

Savings compared to those offered
by optimal, unrestricted solution: 65 %



SOLUTION SUMMARY PAGE

Run title:
Demand Sens. (D-10, 11)

Scenario

Overhead costs: Normal   Transportation costs: - 10 %
Demand level: - 10 %   # of facilities: 11
East Haven remains open, and no expansion at Wethersfield.

Solution

Facilities closed: Brookfield, Higganum

Facilities expanded: None
(# of bays added)

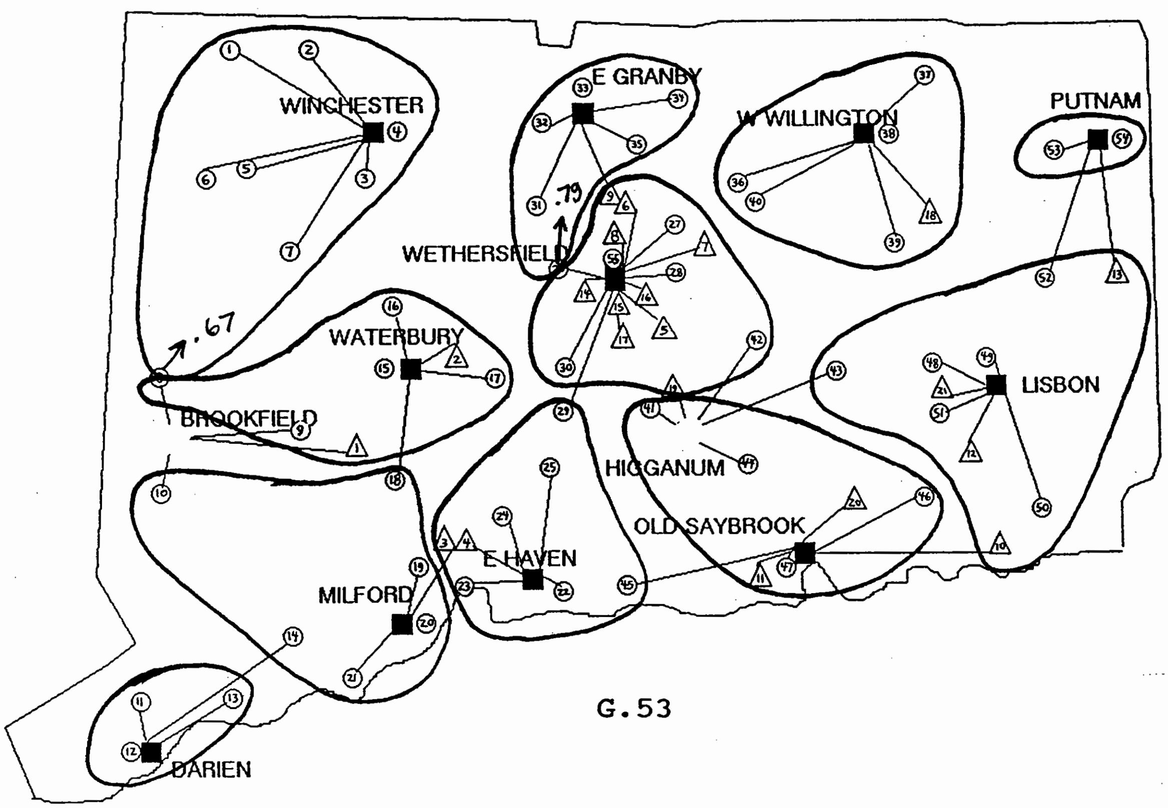
Total annualized cost
(in thousands of dollars): 3653.05

Annualized cost components relative to optimal 13-facility solution (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-510.0	+180.8		-329.2

Net present value of savings: $ 3.5 million

Savings compared to those offered
by optimal, unrestricted solution: 43 %



SOLUTION SUMMARY PAGE

Run title:
Demand Sens. (D-10, 13)

Scenario

Overhead costs: Normal

Transportation costs: - 10 %

Demand level: - 10 %

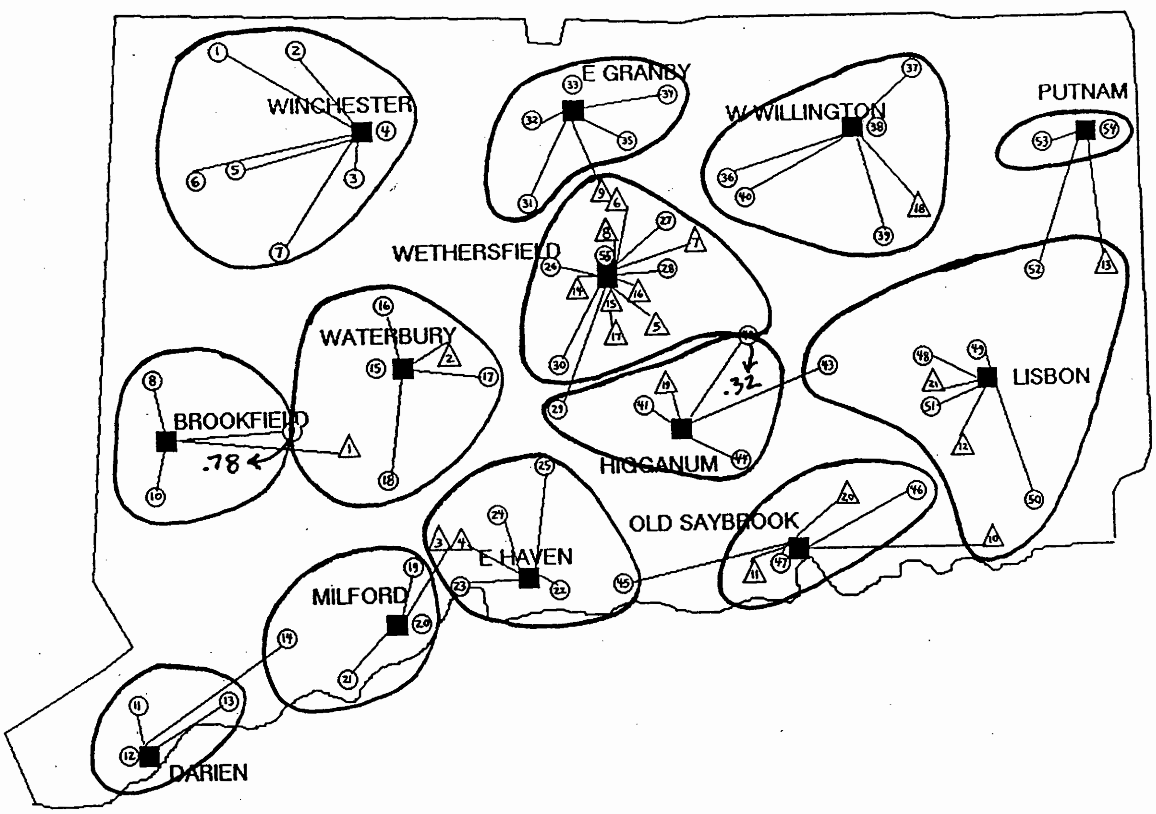
# of facilities: 13

Solution

Facilities closed: None

Facilities expanded: None
(# of bays added)

Total annualized cost
(in thousands of dollars): 3982.22



SOLUTION SUMMARY PAGE

Run title:
Demand Sens. (D+10, unrestricted)

Scenario

Overhead costs: Normal

Transportation costs: + 10 %

Demand level: + 10 %

\# of facilities: unrestricted

Solution

Facilities closed: Brookfield, East Haven, Higganum
East Granby, Darien, Putnam

Facilities expanded: Milford(+10), Wethersfield(+10),
(# of bays added) Waterbury(+6.8), Lisbon (+2.9)

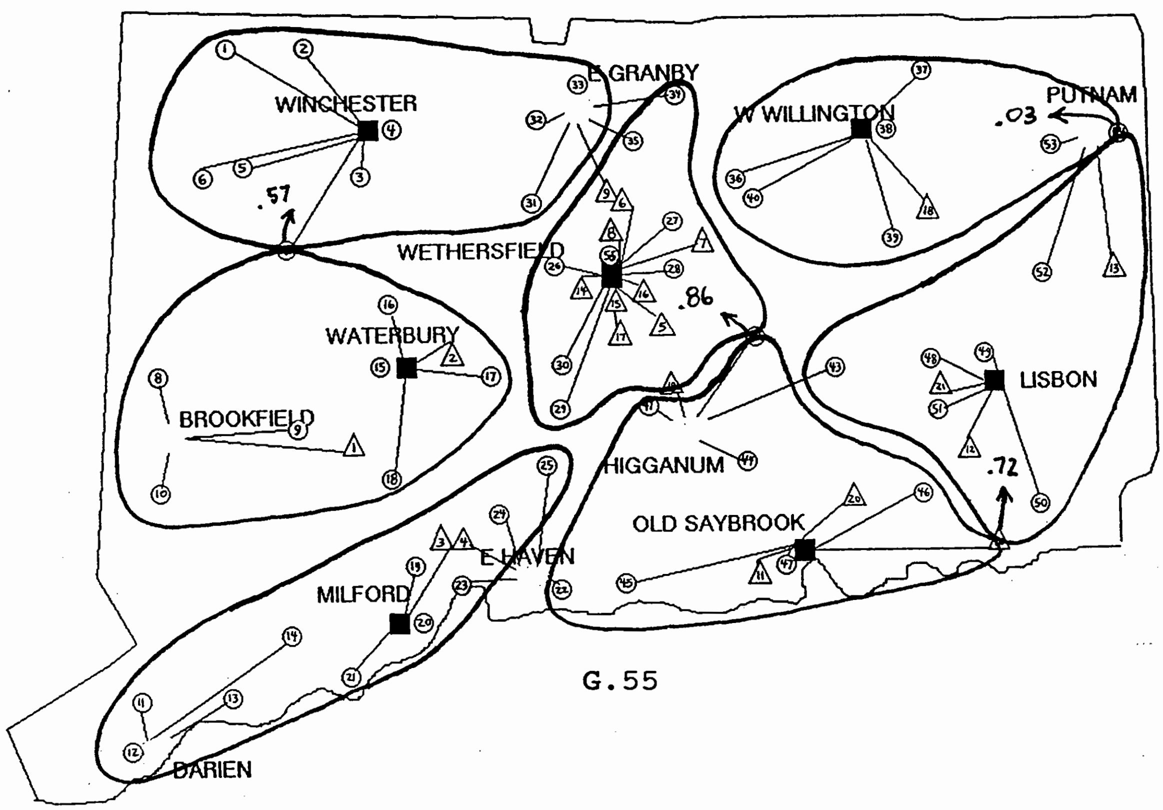
Total annualized cost
(in thousands of dollars): 3703.62

Annualized cost components relative to optimal 13-facility solution (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-1433.4	+609.5	+263.8	-560.1

Net present value of savings: $ 5.9 million

Savings compared to those offered
by optimal, unrestricted solution: 100 %



SOLUTION SUMMARY PAGE

Run title:
Demand Sens. (D+10, 10)

Scenario

Overhead costs: Normal

Transportation costs: + 10 %

Demand level: + 10 %

# of facilities: 10

Solution

Facilities closed: Brookfield, East Haven, Higganum

Facilities expanded: Waterbury, Wethersfield
(# of bays added) (+4.6) (+10)

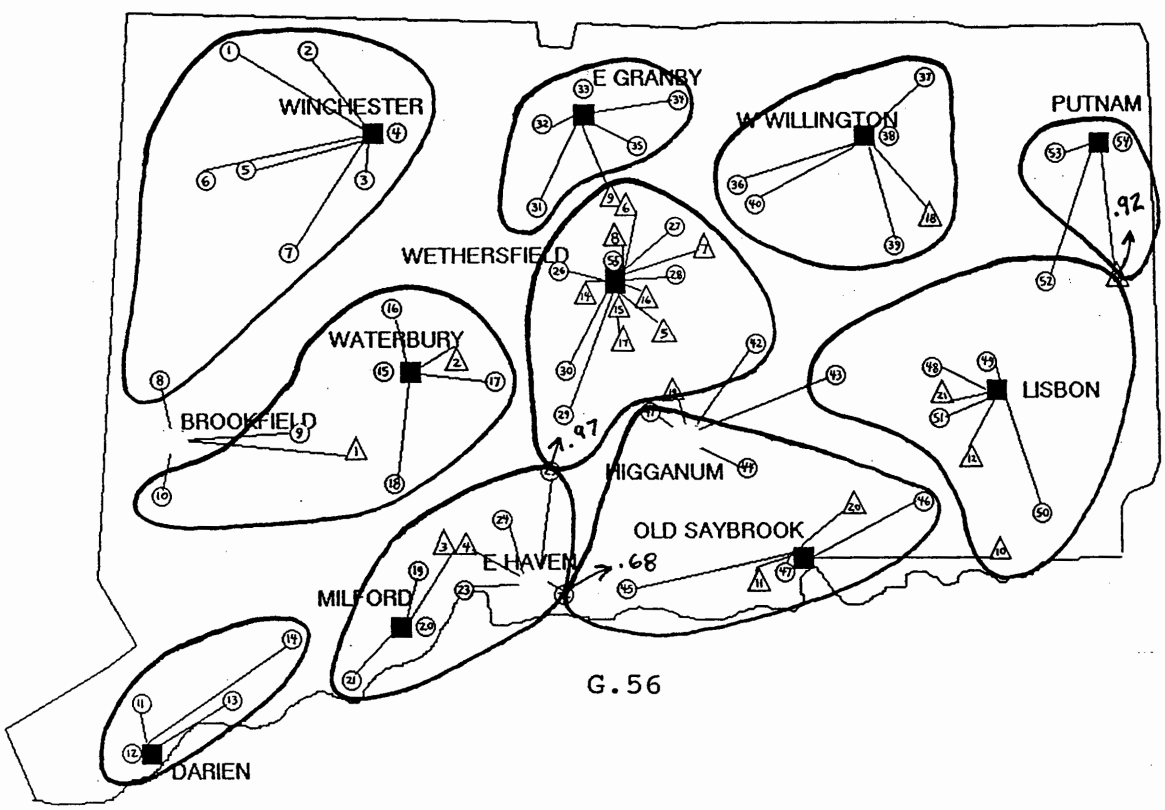
Total annualized cost
(in thousands of dollars): 3844.92

Annualized cost components relative to optimal 13-facility solution (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-795.5	+246.8	+129.9	-418.8

Net present value of savings: $ 4.4 million

Savings compared to those offered
by optimal, unrestricted solution: 75 %



SOLUTION SUMMARY PAGE

Run title:
Demand Sens. (D+10, 11)

Scenario

Overhead costs: Normal   Transportation costs: + 10 %
Demand level: + 10 %   # of facilities: 11
East Haven remains open, and no expansion at Wethersfield.

Solution

Facilities closed: Brookfield, Higganum

Facilities expanded: Waterbury
(# of bays added) (+2)

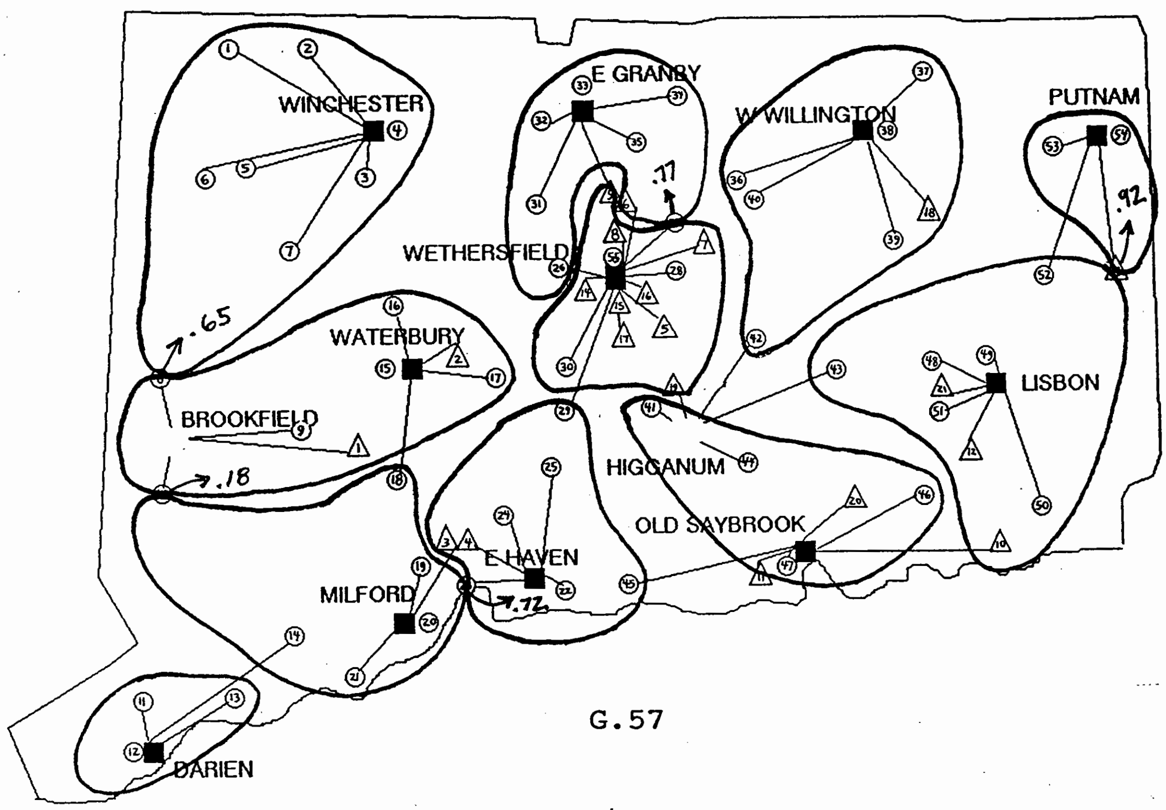
Total annualized cost
(in thousands of dollars): 4003.64

Annualized cost components relative to optimal 13-facility solution (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-510.0	+227.7	+22.2	-260.1

Net present value of savings: $ 2.7 million

Savings compared to those offered by optimal, unrestricted solution: 46 %



SOLUTION SUMMARY PAGE

Run title:
Demand Sens. (D+10, 13)

Scenario

Overhead costs: Normal

Transportation costs: + 10 %

Demand level: + 10 %

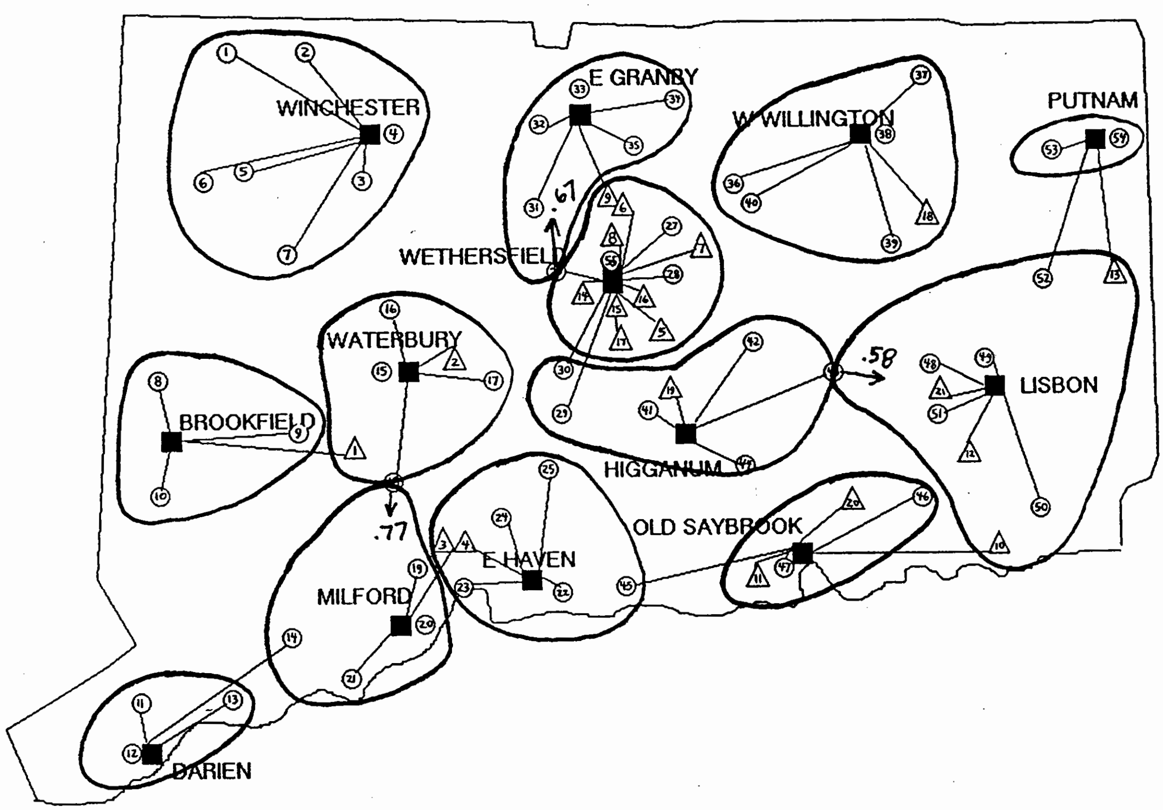
# of facilities: 13

Solution

Facilities closed: None

Facilities expanded: None
(# of bays added)

Total annualized cost
(in thousands of dollars): 4263.65



SOLUTION SUMMARY PAGE

Run title:
Demand Sens. (D+20, unrestricted)

Scenario

Overhead costs: Normal Transportation costs: + 20 %

Demand level: + 20 % # of facilities: unrestricted

Solution

Facilities closed: Brookfield, East Haven, Higganum, East Granby, Putnam

Facilities expanded: Milford(+5.9), Wethersfield(+10),
(# of bays added) Waterbury(+8.9) Lisbon(+2.0), West Willington(+5.3)

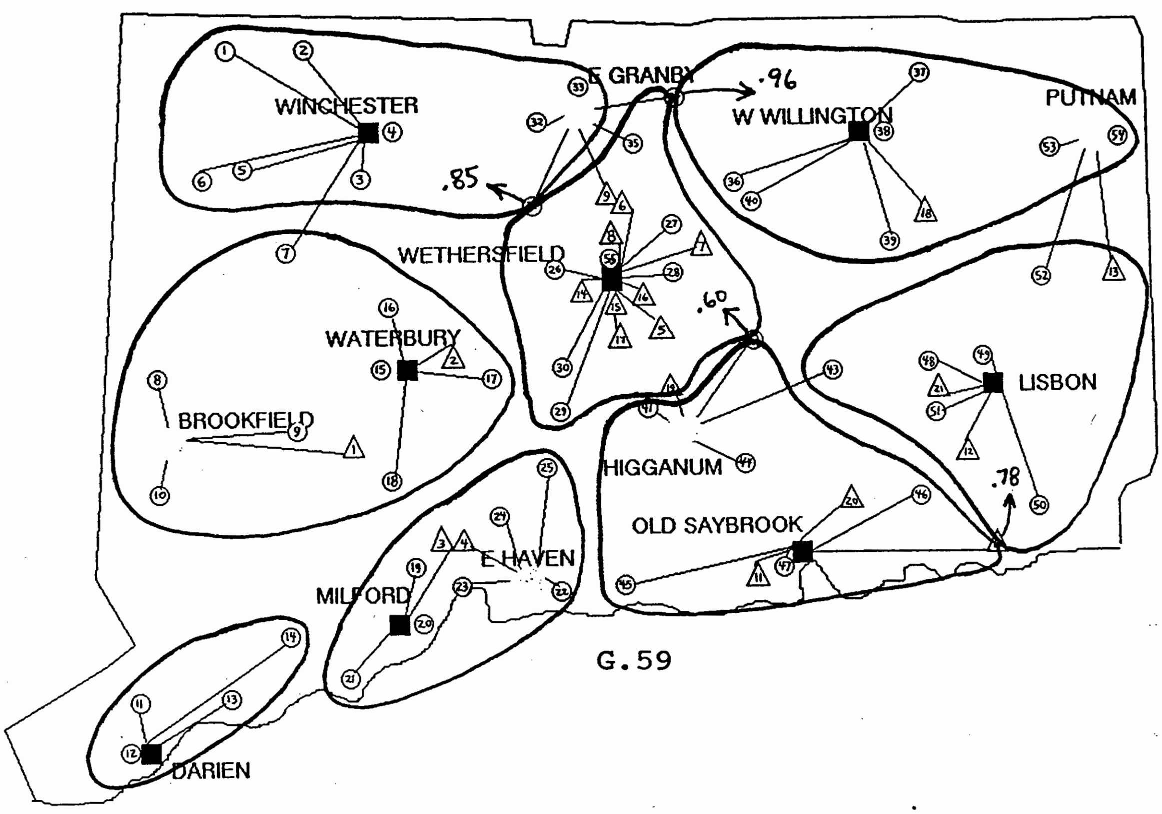
Total annualized cost
(in thousands of dollars): 3983.21

Annualized cost components relative to optimal 13-facility solution (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-1196.9	+521.1	+249.3	-426.5

Net present value of savings: $ 4.5 million

Savings compared to those offered by optimal, unrestricted solution: 100 %



SOLUTION SUMMARY PAGE

Run title:
Demand Sens. (D+20, 10)

Scenario

Overhead costs: Normal

Transportation costs: + 20 %

Demand level: + 20 %

# of facilities: 10

Solution

Facilities closed: Brookfield, East Haven, Higganum

Facilities expanded:	Waterbury,	Milford,	Wethersfield
(# of bays added)	(+6.2)	(+3.9)	(+10)

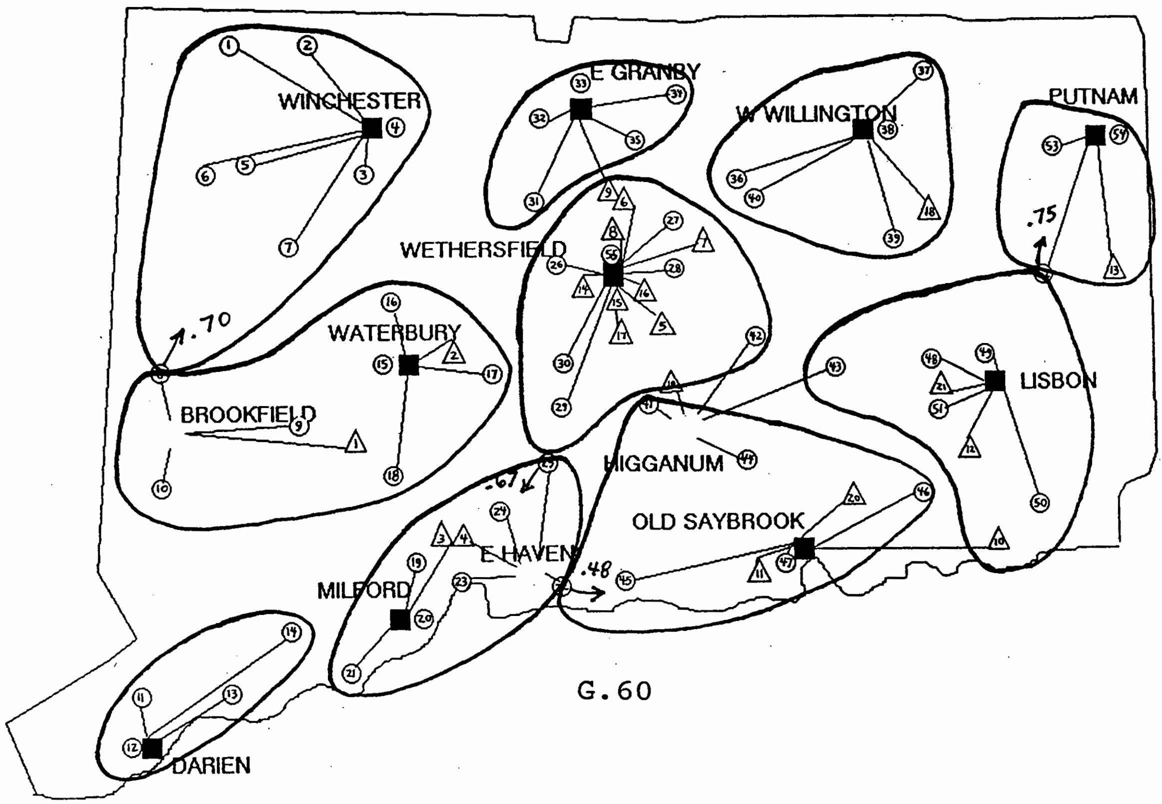
Total annualized cost
(in thousands of dollars): 4045.22

Annualized cost components relative to optimal 13-facility solution (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-795.5	+290.6	+140.4	-364.5

Net present value of savings: $ 3.8 million

Savings compared to those offered by optimal, unrestricted solution: 84 %



SOLUTION SUMMARY PAGE

Run title:
Demand Sens. (D+20, 11)

Scenario

Overhead costs: Normal   Transportation costs: + 20 %
Demand level: + 20 %   # of facilities: 11
East Haven remains open, and no expansion at Wethersfield.

Solution

Facilities closed: Brookfield, Higganum

Facilities expanded: Waterbury
(# of bays added) (+5.1)

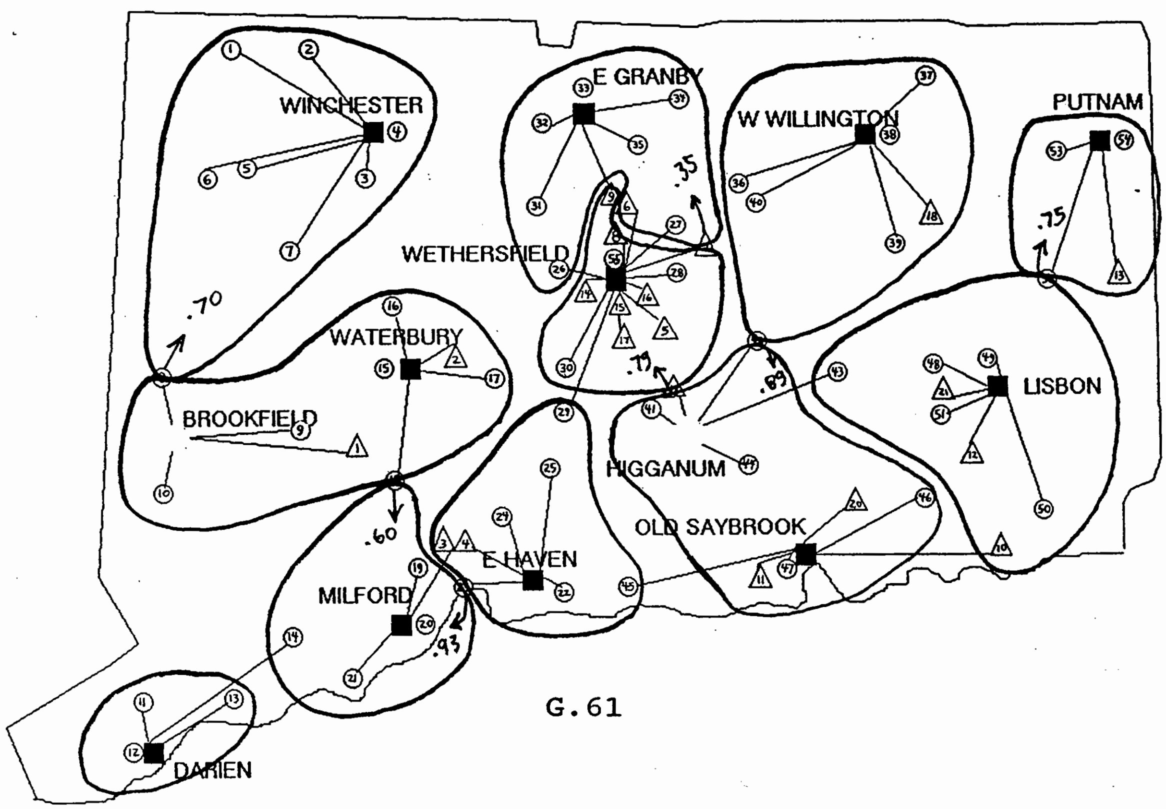
Total annualized cost
(in thousands of dollars): 4186.57

Annualized cost components relative to optimal 13-facility solution (in thousands of dollars):

Overhead	Transportation	Expansion	Total
-510.0	+279.6	+7.3	-223.1

Net present value of savings: $ 2.3 million

Savings compared to those offered
by optimal, unrestricted solution: 51 %



SOLUTION SUMMARY PAGE

Run title:
Demand Sens. (D+20, 13)

Scenario

Overhead costs: Normal   Transportation costs: + 20 %

Demand level: + 20 %   # of facilities: 13

Solution

Facilities closed: None

Facilities expanded: Wethersfield
(# of bays added) (+4.2)

Total annualized cost
(in thousands of dollars): 4409.73