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ENVIRONMENTAL CONTROL SYSTEMS OPTIMIZATION

Environmental Control Systems Optimization

A thesis written at

MCMASTER UNIVERSITY

in partial fulfillment
of the requirements for the
degree of

Master of Mechanical Engineering in Design

by

Gordon Dwight Duda

December 1973

ABSTRACT

The purpose of this project was to demonstrate the usefulness of optimization in the environmental systems field; particularly to improve analytical decision - making techniques for managers.

The result was an aid to formulating budgets, in which the social, technical, political and relatively unknown aspects of environmental control systems could be logically compared.

Additional benefits, in the area of environmental project evaluations were developed using optimization.

A C K N O W L E D G M E N T S

I wish to express appreciation: to Prof. James N. Siddall for his assistance in my work; to the people I visited at the General Motors Technical Centre, and various General Motors plants in Canada and the United States, for their co-operation in my research; and to my cousin, Miss Judy Onich, for her dedicated typing.

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L I S T O F T A B L E S

I. INTRODUCTION

The field of environmental control systems has grown rapidly in size and importance, particularly in relation to industrial operations. During the past decade, North American legislators have enacted laws at the federal, state, and provincial level that affect air and water quality, solid waste disposal, and more recently, noise levels and the general working environment.

The resultant proliferation of complex, often expensive, yet necessary equipment to control internal and external industrial environment has begun to have a small but significant effect on capital expenditures. Public awareness of ecological imbalance between industry and environment, along with current discussion of a potential energy crisis have added other reasons for giving careful selection to environmental control systems.

A new problem faces many supervisors in the engineering field. The development of environmental programs is not a strictly technical problem. Social pressure of the community and constantly changing legislation affect the programs. A public relations project is often required to sell a corporations' approach to the public. The technology for meeting legislation occasionally exists only in an unrefined state. Developing a budget and setting priorities for programs in this field is becoming an increasingly difficult task for engineering departments. During the authors' training period at General Motors from 1967 to 1973, several programs in plant engineering departments pointed out the need for a fresh approach to decision making, particularly with regard to budget allocations.

It is in this area of study that the thesis was developed. At this point the author will review qualifications for working in the environmental field and selecting a particular project; an explanation of the development of the project will then be given.

The author had studied engineering for four years at General Motors Institute, 1967 to 1971. Emphasis was placed on plant engineering topics. The idea of using optimization in engineering budgets was conceived in 1971 at McMaster University. Further topics related to plant engineering and optimization were studied in 1971 and 1972, as background material for this thesis. The development of this project was encouraged by the Director of the Environmental Activities Section of General Motors Corporation, General Motors Technical Centre, and by the present Chairman of the Mechanical Engineering Department at both General Motors Institute and McMaster University.

The project was intended to apply current optimization techniques, available at McMaster University, to the environmental programs at General Motors of Canada, St. Catharines, Ontario. Emphasis was placed on optimizing the relative merits of social, political, and relatively unknown aspects of various programs along with well known technical programs, to produce a capital budget. The budget is hypothetical yet realistic, based on actual programs that are in progress or recently completed. The aim of the author was to develop a tool for decision-makers that would enable a more effective analysis of environmental programs.

The development of this project followed the same basic steps as most optimization problems.

The first step involved selection and detailed analysis of six different programs, representing technical and non-technical variables that could be included in a capital budget. The second step was development of utility curves to express the value of each program, related constraints, and a suitable optimization expression.

It may be valuable to review Ref. (3) concerning these terms. The third step consisted of writing a computer program to demonstrate the optimization process. Social, political, technical and relatively unkown aspects of the variables were handled logically and quickly to result in a practical and workable budget analysis. The last step was to consider the value of the project and its effect on traditional methods of budget development in the plant engineering department (1).

It is necessary to clearly understand the role optimization can play in a budget. By reviewing the latest Statement of Consolidated Income and Consolidated Balance Sheet of General Motors Corporation (7), one can appreciate the complexity of a budget required to handle cash flows resulting from an annual sales of over thirty billion dollars. The author intends to apply optimization to a small portion of non-productive expenses.

As noted in the General Motors 1972 Annual Report (8), approximately only 3 per cent of revenues are retained for use in the business for working capital, expansion, and modernization of facilities.

Within this 3 per cent of revenue, falls expenditures required for environmental control systems, that is; pollution control facilities, and working environment. The need to optimize expenditures in this

non-productive area has always been present, as common sense would indicate.

The escalation of expenditures in the last five years to control industrial pollution (9) and to satisfy union demands and legislation affecting the working environment (10), (8), has created an even greater need for optimizing environmental control systems expenditures.

A formal optimization of the social, political, technical and experimental aspects of environmental systems expenditures at two plants within General Motors Corporation was carried out. The resultant capital budget reflects the large non-productive expense that must be handled by a typical plant engineering department. The budget does not include the normal operating expense of the department, nor is it intended to replace any existing accounting methods used in the productive area of plant operations.

Within this framework, optimization will be used to improve the development of a portion of capital budget expenditures at General Motors of Canada Limited, St. Catharines.

II GENERAL METHOD

The thesis is an attempt to set up a procedure for assisting General Motors engineering management in making an optimal allocation of capital funds for environmental control purposes. It is not always possible to show a monetary return for such expenditures, so the concept of utility functions is used as a basis for the allocation(3)

Utility theory is used to measure the subjective value of various plant design variables or environmental characteristics, such as good will, neighbourhood noise levels, or safety. The plant design variables are considered to be environmental characteristics which contribute to the enhancement of the company's position or future in some non-monetary way. The subjective value of such variables is expressed graphically, as indicated in Figure 1. The term "corporate utility" is used to emphasize the industrial background of the utility curves.

It is then possible to use engineering and cost data to relate the plant design variable to capital cost, shown typically in Figure 2.

The utility curves should be sketched by experienced members of engineering management along with members of Industrial relations and line management. Each person could develop a curve, and the curves should then be aggregated in some manner, such as the DELPHI method (39).

Figure 1.

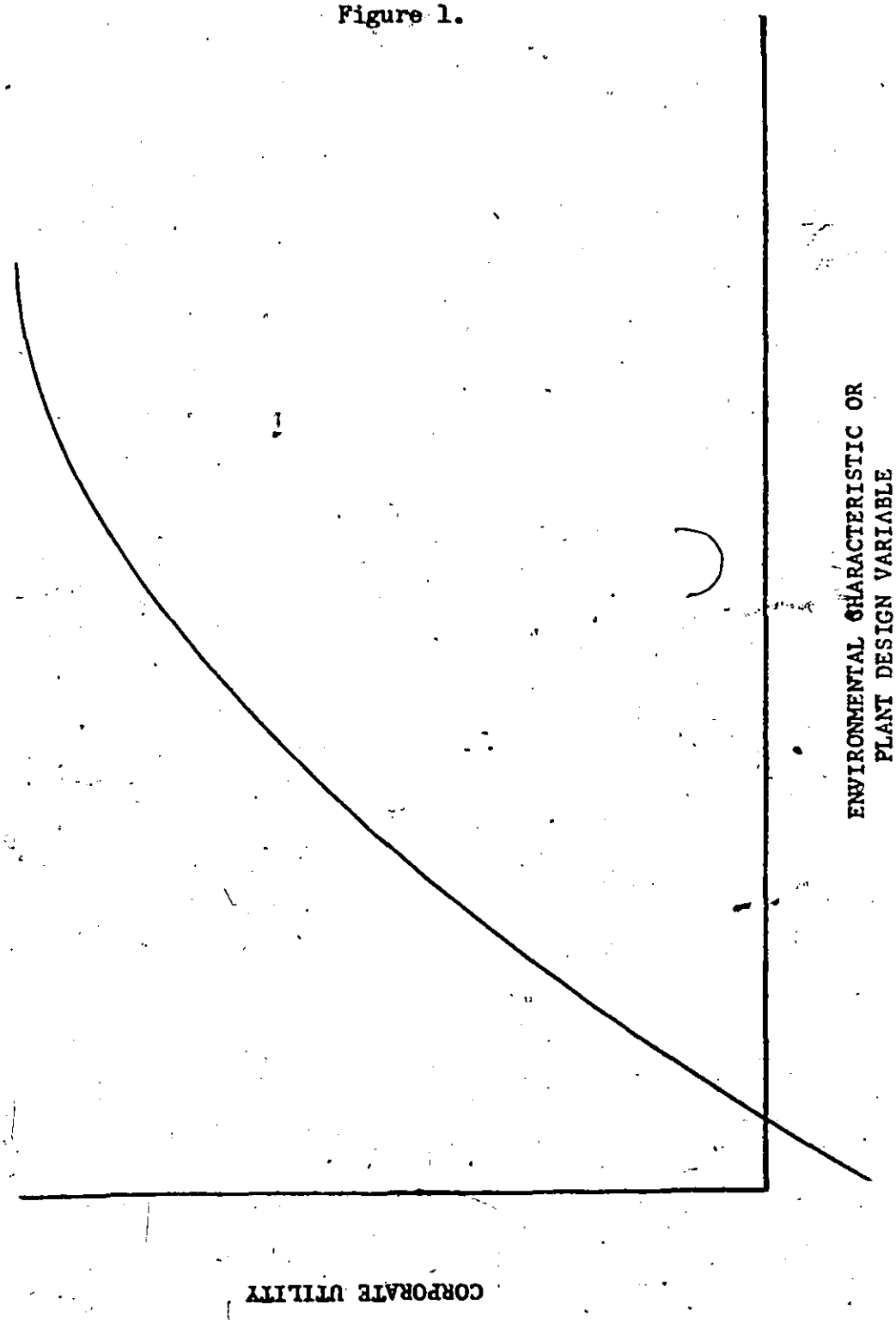
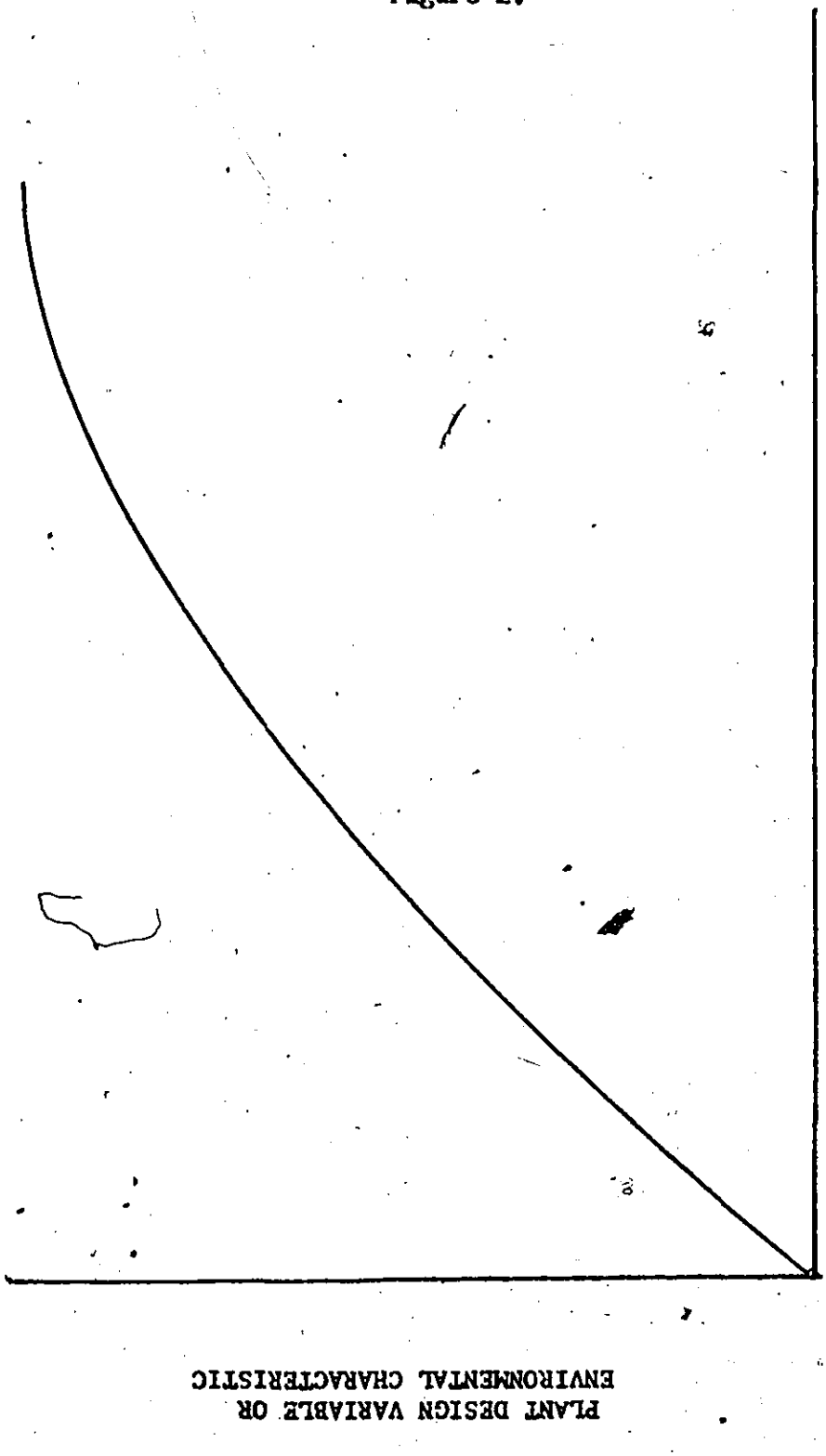

ENVIRONMENTAL CHARACTERISTIC OR
PLANT DESIGN VARIABLE
CORPORATE UTILITY

Figure 2.


CAPITAL COST
PLANT DESIGN VARIABLE OR
ENVIRONMENTAL CHARACTERISTIC

Combining the two curves gives a relationship between capital cost and corporate utility. In some cases, only one curve will be required. These exceptions will be discussed as they appear.

It is desirable to combine the utility contributions of each kind of capital expenditure, and adjust expenditures to maximize total corporate utility. The senior management staff must weight the utility scales to reflect their relative importance to General Motors. The DELPHI method (39) is one means of aggregating staff weighting factors. Standard optimization procedures (4) can be used to maximize corporate utility, and to allocate capital funds.

Allocations will be subject to constraints, such as maximum capital expenditure available overall, and logical maximum expenditures for each environmental characteristic. Other types of budgetary constraints may be applicable: management may wish to limit annual operating expenses arising from a particular capital expenditure, or from all capital expenditures; if there is annual savings resulting from a capital expenditure, the equivalent annual cost may be required to be less than the annual saving; or management may require some minimum annual monetary return from a capital expenditure, even though the primary purpose is for corporate utility arising from environmental control.

This approach can be used for other non-monetary corporate utilities related to items such as safety, employee satisfaction, and housekeeping.

From a mathematical point of view the independent variables are the various capital expenditure allocations, all under the direct

control of management. The dependent variables are the environmental characteristics or plant design variables from capital expenditures.

Within the rather large area of environmental programs at General Motors, two specific areas were selected for study. Five variables were chosen from various aspects of the air pollution abatement program at Plant Three, General Motors of Canada, St. Catharines, which is the only General Motors foundry facility in Canada. One variable was selected from a possible internal environment program at Plant Four, General Motors of Canada, St. Catharines, involving the dynamic use of light and colour. These six variables will comprise a hypothetical budget.

It is important to understand the current state of the art, and applicable legislation for both air pollution abatement and lighting and colour systems. A glance through **Ref. (1) (2) and (22) is** suggested for those readers unfamiliar with this field.

As can readily be seen from **Ref. (1) and (22) the control of air** quality leaving a foundry is fast becoming a science, and the selection of a control system fairly simple from a purely technical standpoint.

The difficult areas in selecting a system from a management view-point often reach beyond the immediate technical selection and can best be illustrated by the questions:

> Will new techniques or equipment be compatible with existing plant facilities?
>
> Can public relations affect the nature of a pollution abatement program:
>
> In view of a potential energy crisis, will the system economically use available resources?

Will the system adapt to more effective air cleaning, if so required by future legislation?

Will the system create water, thermal, or noise pollution as by-products of cleaner air?

Such questions must be studied, before a capital budget can be constructed.

As pointed out in Ref. (2), light and colour can be used to improve: production, safety, visibility, housekeeping, labour relations, employee morale, public relations, and efficiency of lighting. An experimental program will be developed for inclusion in the budget involving these characteristics of light and colour.

Note that the plant design variables do not comprise a complete capital budget for General Motors of Canada, but are typical and illustrate adequately the techniques developed by the author. A complete capital budget could not be revealed in order to protect the interests of General Motors Corporation.

A final point worth mentioning is that the subjective nature of the value-judgements discussed above makes their quantification rather difficult. Values vary from individual to individual, and in time; however, with the development of reliable techniques for evaluating "corporate utility", these concepts can be a valuable asset in decision-making.

III. VARIABLES USED IN OPTIMIZATION

Six variables were selected for optimization. Each represents a capital expenditure for an environmental system that could be included in a forthcoming budget. The variables will be mathematically coded, for later use in the optimization computer program:

X(1) Good Will - the value received from a significant public relations effort concerning air pollution.

X(2) Operating Cost Savings - selection of dust collectors with emphasis placed on minimizing service and maintenance expenditures.

X(3) Adaptability - selection of cupola emission control equipment - justification of additional expenditures to provide capacity for more efficient operation, as foreseen by the legal advisors.

X(4) Noise Reduction - growing importance and cost of controlling noise that effects public and private property around an industrial plant.

X(5) Roof - expenditures on roof mounted equipment that affect internal and external plant air distribution.

X(6) Productivity - a project experimenting with the use of light and colour to significantly improve productivity, safety, housekeeping, and labour relations.

The variables were chosen specifically to bring in to focus the more difficult aspects of budget development for a modern engineering department at General Motors: analytical evaluation of non-technical and semi-technical variables; significance of an experimental variable; logical comparison of all variables; limited budget; and constant changes to a budget during its development. Each variable will be developed in reasonable detail.

Exact costs and some sources of figures used in this thesis can not be revealed in order to comply with the wishes of General Motors of Canada.

Variable X(1) Expenditure for Public Good Will

Of concern here is the corporate utility generated by public good will based on what General Motors believes to be the company's ecological merit.

As was noted in the previous chapter, a public relations program may have some influence on public sentiment and legislation concerning a foundry air pollution abatement program, both as to content, timetables and effectiveness.

Public good will towards the company is a measurable environmental characteristic but expensive to measure; therefore, dollar expenditures were used directly with utility.

Assume that the following costs represent results of a study undertaken by the public relations department. A $50,000.00 expenditure would be required to develop and mail out a reasonably comprehensive progress report to residents in the city of St. Catharines, every six months. The purpose of the report would be to convince the community that General Motors is cleaning up its foundry in a reasonably paced program.

No other significant effect would occur as the expenditure increased until it reached $500,000.00. At this point the public relations effort could embrace progress reports, aid in development of provincial laws, and aid in public research aimed at preventing action towards a zero-discharge of pollutants.

At one end of the scale public relations can inform the community and at the other end, modify legislation that would demand very expensive and perhaps unnecessary pollution abatement facilities.

Variable X(1) represents a non-technical item that has value in an engineering budget.

Variable X(2) - Operating Cost Savings from a Dust Collector

The plant design variable in this case is the operating cost saving from operation of a dust collector. Although this technical variable can be handled by a conventional cost benefit analysis, it has been included in the capital budget to demonstrate the flexibility of optimization to handle a traditional item, along with non- technical and experimental types of budget allocations.

Assume that an engineering study has determined that an exhaust system for a shakeout line requires a 50,000 C.F.M. capacity dust collector. Wet type dust collectors of this type and capacity are common in the foundry, particularly a 46,000 C.F.M. model made by the Schneible company.

Three different collectors are available for use on this particular application. A dry fabric type dust collector costs $ 50,000.00. A comparable efficiency wet centrifugal collector (outlet loading 0.01 grains per standard cubic foot) costs $ 55,000.00; and an older style similar to existing equipment costs $ 60,000.00 if constructed for comparable efficiency. The latter style collector is desirable from a maintenance standpoint since spare parts are already in stock and maintenance procedures are thoroughly understood.

Both wet collectors would have reduced operating costs since their effluent could flow into existing troughs leading to existing water treatment facilities. The wet collectors consume similar amounts of energy.

The handling of dry dust from the fabric collector would require a seperate treatment system and additional labour costs for disposal.

Either type of collector would save at least $ 100.00 per year in maintenance costs, currently spent to clean the roof of particulate matter emitted by the overworked dust collection system currently in use. A table relating initial costs to operating cost savings is included. Operating cost savings reflect energy use, maintenance and effluent disposal.

Table 1

Collector	Initial Cost	Operating Cost Savings
Fabric	$ 50,000.00	$ 100.00 per year
Wet-New Type	$ 55,000.00	$ 600.00 per year
Wet-Existing Type	$ 60,000.00	$ 800.00 per year

One would expect that the selection of a dust collector would be based on the lowest combined initial and operating costs for the lifetime of the equipment, set at ten years in this case.

Several other influences can affect the selection: low initial project cost to win a corporate job tender, long term plan to standardize equipment throughout the foundry, or a drive to reduce maintenance budgets . The last factor dominates in the case of variable X(2).

Variable X(3) - Adaptability to Future Legislation

The environmental characteristic here is particulate collection efficiency.

A current excerpt from Ontario Regulation 288/69 states that "all ferrous foundry operations shall be designed and operated so as to have a minimum particulate collection efficiency of 97 per cent (by wt.) of the plus 25 micron fraction."

This apparently stringent legislation does not remove from sight all of a foundry's plumes, nor does it keep all of a foundry's particulates from settling on neighbourhood cars and homes. The environmental movement is active at both community and government levels. It is possible then, that the efficiency requirements will increase in the future; discussed at the federal level in the U.S.A. are various "zero discharge bills" requiring 100 per cent removal of contaminents in all plant effluents (12).

Management may consider an extra expenditure on air pollution equipment to ensure that it can be useful when efficiency requirements go up. Examples would be: enlarging wet centrifugal dust collector casings to allow for future impingement stages, designing cupola emission systems with space for extra electrostatic precipitating plates, a larger conditioner, or deeper layer of filtering media. It may be uneconomical, in the long run, to install equipment that can not be efficiently modified in the future.

Of particular concern is a $ 1,000,000.00 cupola emission control system recently installed in the foundry, designed to meet the current requirements of 97 per cent particulate removal, or

25 lb. maximum emission per hour of particulates per cupola. Eventual residential development around the foundry may cause the provincial government to enforce an existing regulation dealing with ambient air quality that may require a higher efficiency (13).

By internally modifying the system and increasing the pressure drop through the venturi scrubber from a current 50 inches of water to 70 inches of water the efficiency can be raised to 97.5 per cent. The cost involved for new fans, motors, sound insulation, services, and other related items estimated at $ 20,000.00. An addition of $ 175,000.00 to the capital expenditure would allow for later installation of a conditioner and electrostatic precipitator to replace the venturi scrubber and allow an efficiency level of 98.5 to 99.0 per cent. The breakdown of costs involves: $ 50,000.00 for rearranging equipment; $ 50,000.00 for structural modifications of building to handle the future weight and size of the equipment, which will be mounted well above floor level; $ 50,000.00 to increase the size and acoustic effectiveness of the enclosure for the emission project; and $ 25,000.00 to increase the capacity of related water cooling towers, sludge removal and waste treatment facilities.

Note that such re-working of a system after initial installation would be difficult, very costly, and necissitate significant downtime of the cupola. On this basis the potential efficiency of an emission control system can be considered fixed at the time of installation.

In order to realistically approach 100 per cent particulate removal at this foundry, one can only surmise that an entirely new approach will be required that may be added or that may replace the current system. Based on research that indicated an exponential rise in cost as efficiency approached 100 per cent, provision for 100 per cent efficiency was estimated to cost $ 900,000.00. As utility curves and constraints are presented it will become clear that a more accurate estimate is unnecessary. Variable X(3) introduces the idea of uncertain legal requirements into the budget. The costs are summarized in a table.

Table 2

Potential Efficiency	Cost involved to provide potential efficiency
97 per cent	0
97.5 per cent	$ 20,000.00
98.5 per cent	$ 175,000.00
100.0 per cent	$ 900,000.00

Variable X(4) - Noise Reduction

Although noise levels have been clearly specified for the inside of a plant, the noise levels on the outside, particularly roof mounted air pollution abatement equipment, have not been as clearly specified. Noisy dust collectors and cupola emission control equipment, from high duct velocities and large power drive sources can annoy neighbours for miles around, depending on the topographical and atmospheric conditions. For good public relations, and because some present regulations require and probably all future regulations will require, these noise sources should be controlled. This leads

to noise reduction as an environmental characteristic or plant design variable.

It may be difficult to determine the sound carrying problems unique to the plant area; the amount of money to be spent on noise control will depend on the size of risk management is willing to take in terms of present and future noise violations, and on the sound levels that management feel they can get away with and not receive neighbourhood complaints. In any case it is less expensive to design quietness into a system that to tack it on as an afterthought.

The type of equipment involved may be stack silencers, sound insulation, enclosures, redesigning ducting, alternate air cleaning methods, or modified power sources.

Consider a recent installation of a cupola emission control system in the foundry, which used an 800 horse power electric motor to drive a fan capable of producing a 50 inch of water pressure drop in the venturi section. Noise levels reached 105 to 110 decibels on the A scale at 5 feet from the noise sources.

Since noise produced by a roof-mounted system dissipates to a safe level by the time it reaches floor level inside the building, concern for noise reduction on roof-mounted equipment has not been significant. In this case, however, the noise did generate complaints from as far as two miles away. The foundry may, in the future be surrounded by residential areas, which could cause creation of a local by-law restricting noise levels at the property line. Such a by-law affects the General Motors transmission plant in Windsor and is being considered for Plant Four in St. Catharines. Noise

levels proposed in the latter case are in the range of 55 dba in daytime and 45 dba at night. (14)

It is of value to consider additional initial capital expenditure to quieten an emission control system at installation and to study future development plans of the community.

A reasonable noise level reduction at this time is 0 dba to 15 dba. Related costs and necessary action are included in Table 3.

Noise Level Reduction	Item Number	Method	Cost
2dba	1	larger duct, slower fan	$ 20,000.00
4dba	2	Item 1 plus exhaust duct stack silencers	$ 45,000.00
6dba	3	Item 2 plus improved acoustical siding in enclosure	$ 85,000.00
15dba	4	Item 3 plus major design refinements	$ 335,000.00

Table 3

Note that the costs tend to rise exponentially. A noise reduction of 3 dba requires halving of noise energy output; therefore, a 15 dba reduction represents elimination of more than 96 per cent of noise energy. This information helps explain the exponential cost function.

Along with technical information, engineering management must consider future residential planning of the city of St. Catharines, and consider the noise limits tolerable to citizens within hearing distance of the almost continuous foundry operation.

Variable X(4) will bring community planning and involvement into the engineering budget, in an analytical fashion.

Note that the costs of including noise reduction consideration at time of installation are far less than the cost of modifying a system after installation. The costs are such that an analysis of present verses future expenditures, considering the time value of money, is unnecessary.

Variable X(5) - Roof Condition

The foundry of General Motors, St. Catharines, has undergone extensive renovation and expansion during the past ten years. Several roof elevations co-exist to house various foundry operations. The constantly changing roof line, complete with roof mounted air exhaust stacks and fresh air intakes has generated several problems.

Occasionally plumes from the many exhaust stacks behave contrary to expectation, in terms of inversions. From time to time exhaust stack height locations must be changed. As plant expansion has taken place there have been instances where, under certain weather and wind conditions, some exhaust air has been drawn into fresh air inlets in sufficient quantities to allow dispersion into the plant interior. Dispersion of exhaust emissions into the atmosphere does not always occur. Occasionally, when a southwest wind prevails, there is an uncomfortable environment in the parking lot area in front of the building.

The surest way to determine optimum stack heights involves a professional meteorological and topographical study (5), (6). The old rule of thumb for estimating stack heights as a certain fraction of building height is insufficient, for all but the most ideal situation. (15)

Let us assume that two items need to be analyzed for inclusion in the budget; one involves relocating exhaust-intake relationships to satisfy the Industrial Safety Act of Ontario, 1971 (16) concerning intake of exhaust air; the other involves labour union complaints of the parking lot environment.

It is not possible to identify a measurable environmental characteristic for the roof condition, as it is necessary to relate capital cost directly to corporate utility arising from improvements in the roof condition.

Table 4

Item	Priority	Cost
Inlet-Exhaust Relocation	Must satisfy legislation	$ 40,000.00
Stack height changes to improve dispersion and outside air quality	To satisfy union demands	$ 10,000.00 professional study and up to $ 200,000.00 for stack changes

Variable X(5) encompasses, as shown in the table, both a required expenditure and a union demand; expenditures that require analysis in an engineering budget.

Variable X(6) - Light and Colour

The impact of light and colour on man in his working environment appears to be significant and has received some in-depth study, as demonstrated in **Ref. (2).** Although the effects of light and colour can be discussed qualitatively; it has been difficult to discuss quantitative effects for a given application. Several supervisors in the plant engineering department at Plant Four, St. Catharines, have expressed interest in a practical application of light and colour. For this reason an in-depth study was under-taken to relate productivity, housekeeping, safety, and labour relations to a light and colour program. Since legislation such as OSHA in the United States requires expenditures in these fields, it is advantageous to optimize any economic return that is possible. The area chosen for study was a 22,800 square foot portion of the rotor machining department 44602-01 in

building one of Plant Four, General Motors, St. Catharines. The area includes operations 10,20 and 30. Twenty-two men are required on a two shift basis to operate the highly automated machines. Minor maintenance problems and frequent machine adjustments require the presence of skilled tradesman and toolsetters, while interrupting machine production several times per shift. The lighting level averages from 20 to 40 footcandles; the machinery is a uniform grey; the ceiling area is a light green colour. Grievances submitted by these employees average less than one per year; their safety record is excellent; and housekeeping is generally quite good. Due to the nature of the machinery the operators can usually load parts onto the equipment faster than the equipment can use it. The operator is not the bottleneck of production.

The rotor machining area is certainly not one in which bright lights and cheerful colours can stimulate employees towards a 25 per cent, 15 per cent or even 10 per cent increase in productivity, but it is representative of a typical automated machining line, that requires few people, and is capable of producing several thousand units per day, to a tolerance measured in ten-thousand's of an inch.

Productivity can be increased through elimination of downtime; contributions can be made to this end if operators notify appropriate personnel quickly about problems; if toolsetters perform their tasks more efficiently and if skilled tradesman can see and enact repairs with a minimum of hesitation. Realistic improvements in production due to light and colour, and based on analysis of a typical working day are estimated to be one to three per cent. (20)

Safety and labour relations improvements are expected to be minimal, but housekeeping may improve noticeably. (2)

These conclusions are conservative. They will form a practical starting point for an experimental program to be considered in the budget. The results of such a pilot program will hopefully give credence to the initial assumptions, and thus, will provide plant engineering supervisors with an accurate means of predicting a plant wide light and colour program.

The light and colour program is listed as five steps, in order of decreasing contribution to productivity,(2) and as assumed by the author. Annual operating costs have also been included.

Table 5

Step	Description	Capital Cost	Operating Cost includes maintenance
1	Raise average light level to 70 footcandles	$ 31,500.00	$ 9,500.00
2	Paint ceiling white	$ 3,000.00	$ 1,000.00
3	Paint machinery cheerful colours	$ 6,000.00	$ 600.00
4	Adopt A.N.S.I. colour code in full	$ 2,000.00	$ 200.00
5	Housekeeping improvement (light & colour improvement to employee eating and working facilities	$ 2,500.00	$ 250.00

The development of this table is explained in Appendix B.

Variable X(6) includes an experimental item to be included in the plant engineering budget. There are then, four plant design variables or environmental characteristics associated with the light

and colour program. They are productivity increase, per cent housekeeping improvement, per cent safety improvement, and per cent improvement in labour relations.

Each variable contributes to total corporate utility. The expected upper limits of the variables are: 3 per cent increase in productivity; 5 per cent increase in plant safety; 10 per cent improvement in labour relations; and 100 per cent improvement in housekeeping. The value of productivity increases can be measured in dollars; the value of the other three plant variables is more subjective, but significant, in a year that saw General Motors open house to the public; union negotiations, and a vigorous safety campaign.

IV. DEVELOPMENT OF UTILITY CURVES FOR VARIABLES

A review of Reference (3) concerning value theory would be useful at this point, for persons unfamiliar with the topic.

There are, of course, several methods of evaluating and scaling utility. Notable methods include the Von Neumann - Morgenstern Standard gamble (23), the Ranking method (28),(29),(30), Equivalence grouping (28),(30), Direct magnitude estimation (34),(35), and the graphical method (3). A comparison of these methods can be found in the Health Status Indexes (36). The selection of a particular method depends on the problem, the decision-maker, accuracy required, and time allowed for evaluation. The author felt that the graphical method was most appropriate for the budget problem of this thesis.

A decision was then made by the author to use linear scaling(3), a simple method of setting up the scale of utility on a utility curve. An alternate method would be ratio scaling (37). Different methods are available to sketch utility curves using linear scaling with the graphical method, such as the Zero-max technique (3) and Harrington's method (25). The Zero-max technique was selected as the more appropriate method for the budget allocation problem.

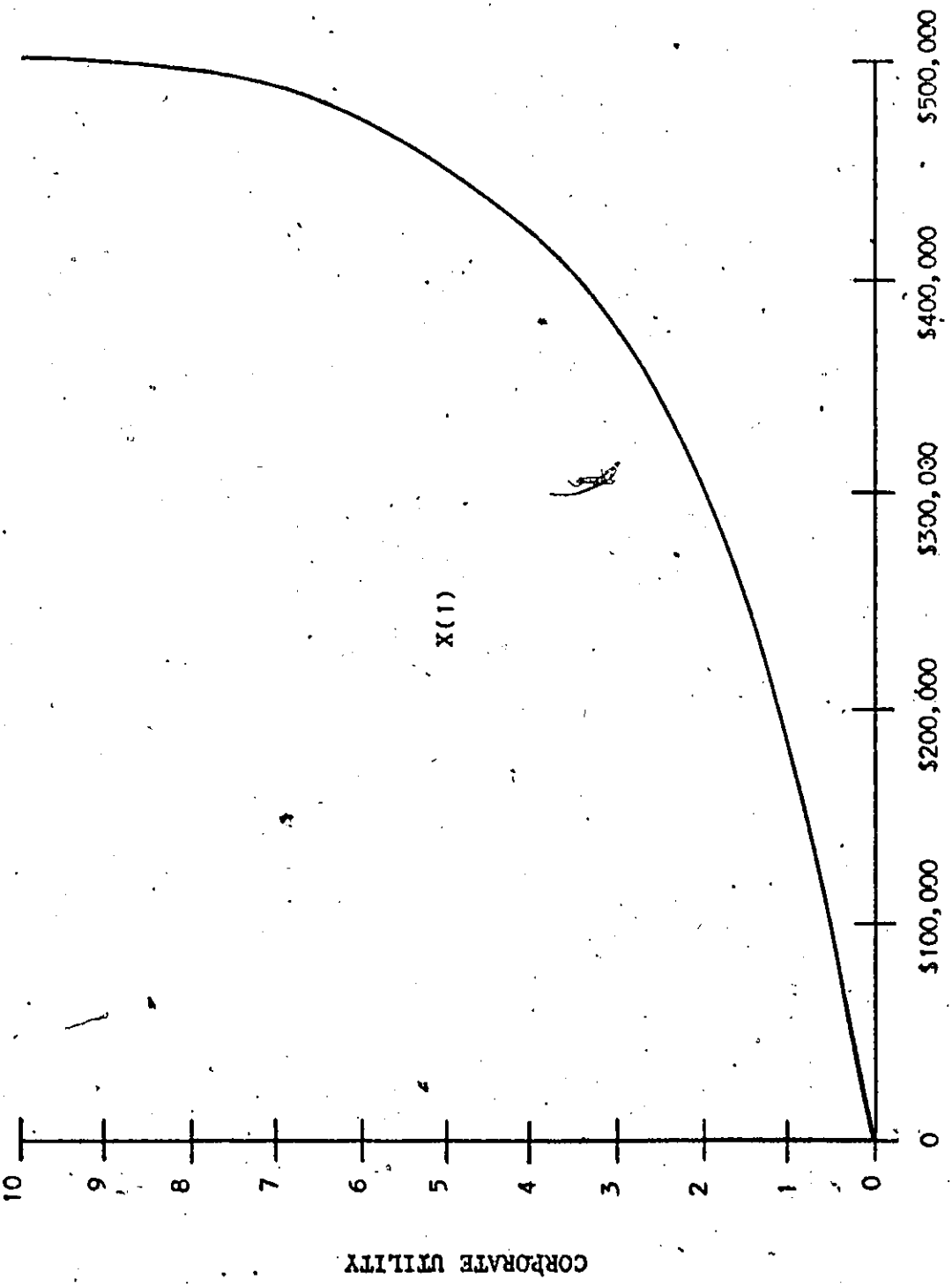
The technique involves selection of an arbitrary but consistent scale of utility; the scale of 0 to 10 is used in this thesis. Reasonable minimum and maximum values are assigned the values 0 and 10, respectively. Intermediate values are then plotted and a continuous curve representing the subjective utility of all intermediate points is drawn.

The utility curves developed in this chapter can be considered the aggregate curves developed by engineering management, line management, and Industrial relations people.

Utility Curve - Variable X(1) - Public Relations

The logical end points for the abscissa of the utility curve can be the upper and lower limits of the study on public relations, $ 0 and $ 500,000.00. In all cases the scale of utility will be initially set from 0 to 10. Since the utility value of a public relations program has only two basic goals, effectively informing the public for $ 50,000.00 at one end, and influencing legislation for $ 500,000.00 at the other end, the curve must resemble a step function. Money spent in excess of $ 50,000.00 and less than, say, $ 400,000.00 contributes little utility value; that is, there is little value in overinforming the community, and not enough has been spent to affect legislation. Thus the curve is assumed to rise slowly up to the $ 400,000.00 point, then utility will increase rapidly to the $ 500,000.00 limit, the region in which legislation can be influenced.

Figure 3


CORPORATE UTILITY
0
1
2
3
4
5
6
7
8
9
10
X(1)
0
$100,000
$200,000
$300,000
$400,000
$500,000
COST OF PUBLIC RELATIONS PROGRAM

Utility Curve - Variable X(2) - Operating Cost Savings

As mentioned earlier, the ordinate of most utility curves will be set initially from 0 to 10, corresponding to reasonable upper and lower limits of each variable placed on the abcissa. However, in the case of variable X(2), an expenditure of at least $ 50,000.00 appears certain; therefore, the cost will range only from $ 50,000.00 to $ 60,000.00 and corresponding utility will be set at 0 to 10.

The limits for operating cost savings have been established at $ 100.00 per year and $ 800.00 per year. Remember that utility curves reflect only the desirability of variable X (2) without regard to capital cost restrictions. This utility curve is a straight line function; the more savings, the better, with each gain of savings possessing the same utility as the last.

The relationship of capital cost expenditures on a dust collector as a function of operating cost savings is necessary if a capital budget allocation is to be made. The table relating these items was developed earlier, but is reproduced in this section along with a curve presenting the same data.

Table 1

Collector	Initial Cost	Operating Cost Savings
Fabric	$ 50,000.00	$ 100.00 per year
Wet-new Type	$ 55,000.00	$ 600.00 per year
Wet-Existing Type	$ 60,000.00	$ 800.00 per year

Figure 4

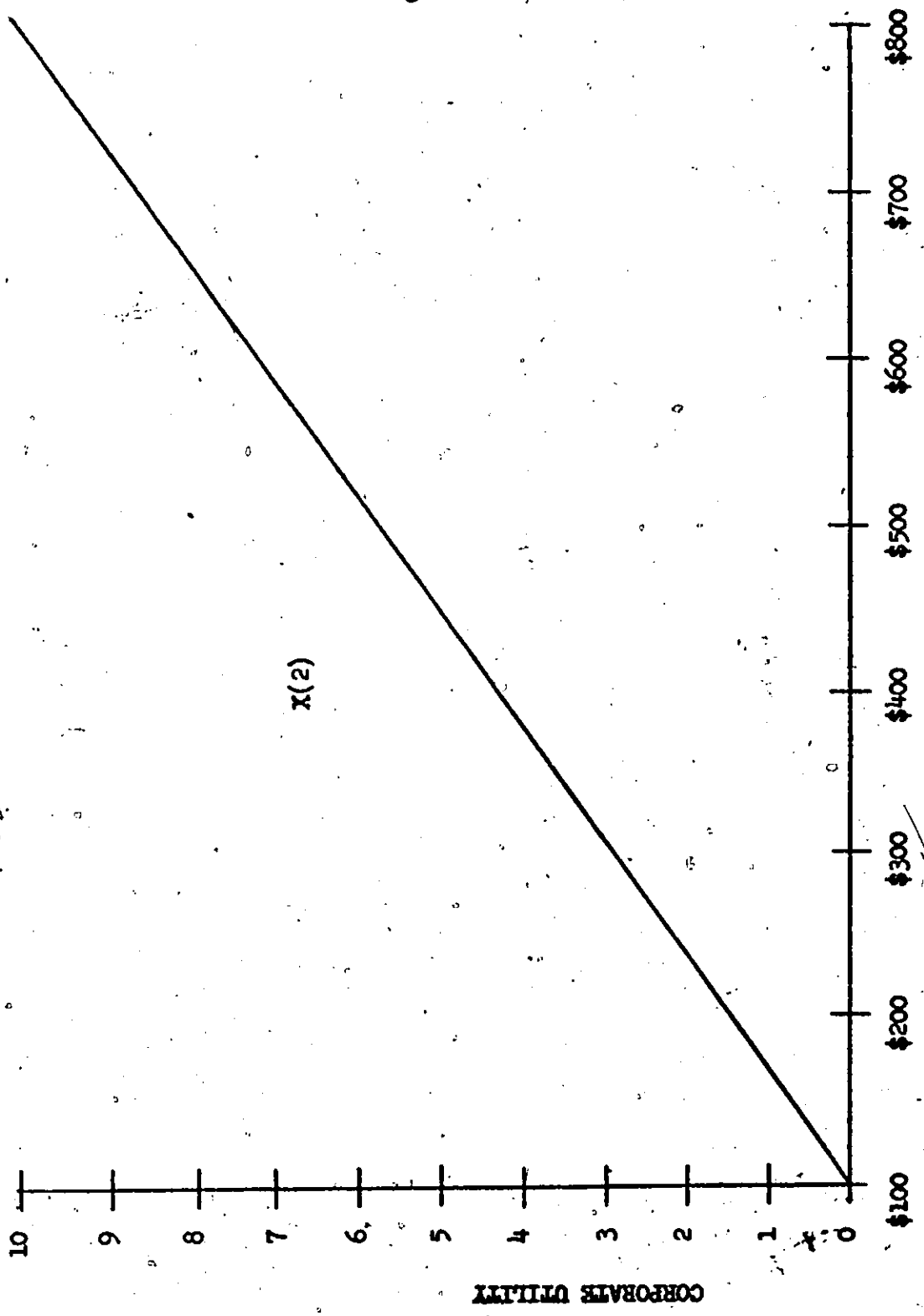
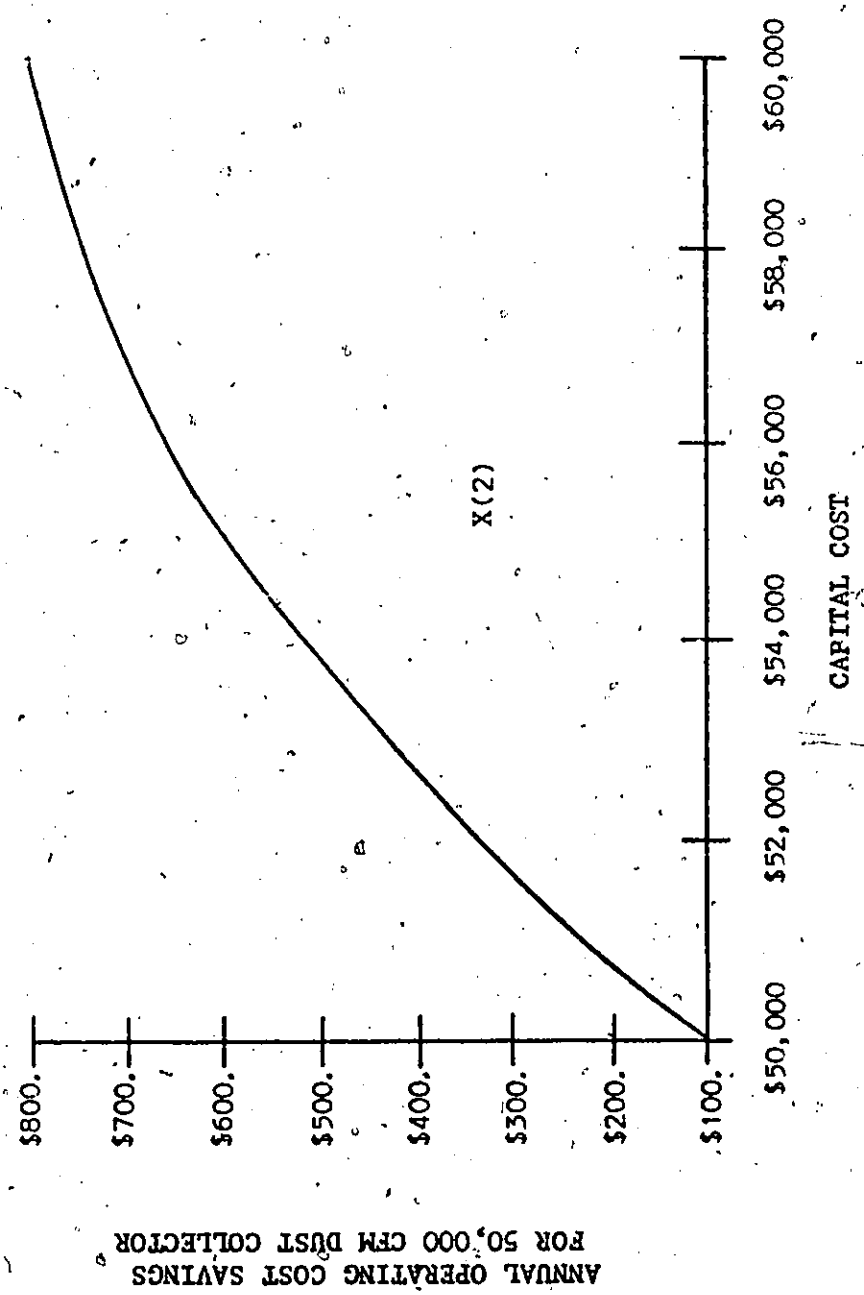

CORPORATE UTILITY
0
1
2
3
4
5
6
7
8
9
10
X(2)
$100
$200
$300
$400
$500
$600
$700
$800
ANNUAL OPERATING COST SAVINGS FOR
50,000 C.F.M. DUST COLLECTOR

Figure 5


ANNUAL OPERATING COST SAVINGS
FOR 50,000 CFM DUST COLLECTOR
$800.
$700.
$600.
$500.
$400.
$300.
$200.
$100.
$50,000
$52,000
$54,000
$56,000
$58,000
$60,000
CAPITAL COST
X(2)

Utility Curve - Variable X(3) - Adaptability

Corresponding to the utility range from 0 to 10, the previously established end points for variable X(3) are 97 per cent and 100 per cent particulate removal efficiency for the cupola emission control unit. The possibility of legislation requiring 98.5 per cent efficiency from the St. Catharines foundry is possible but the possibility of 100 per cent efficiency requirements seem remote during the lifetime of the cupola. Therefore, utility increases rapidly up to the 98.5 per cent point and then slowly as 100 per cent is reached. The utility curve reflects this varying emphasis on different levels of efficiency.

As was required for variable X(2), and will be required for variable X(4) and X(6), the relationship between the variable X(3) and utility and capital cost require two seperate curves. Variables X(1) and X(5) relate capital cost directly to utility since the plant design variables could not be measured directly. Table 2 is presented again, along with the resultant cost curve.

Table 2

Potential Efficiency	Cost involved to provide potential efficiency
97 per cent	0
97.5 per cent	$ 20,000.00
98.5 per cent	$ 175,000.00
100.0 per cent	$ 900,000.00

Figure 6

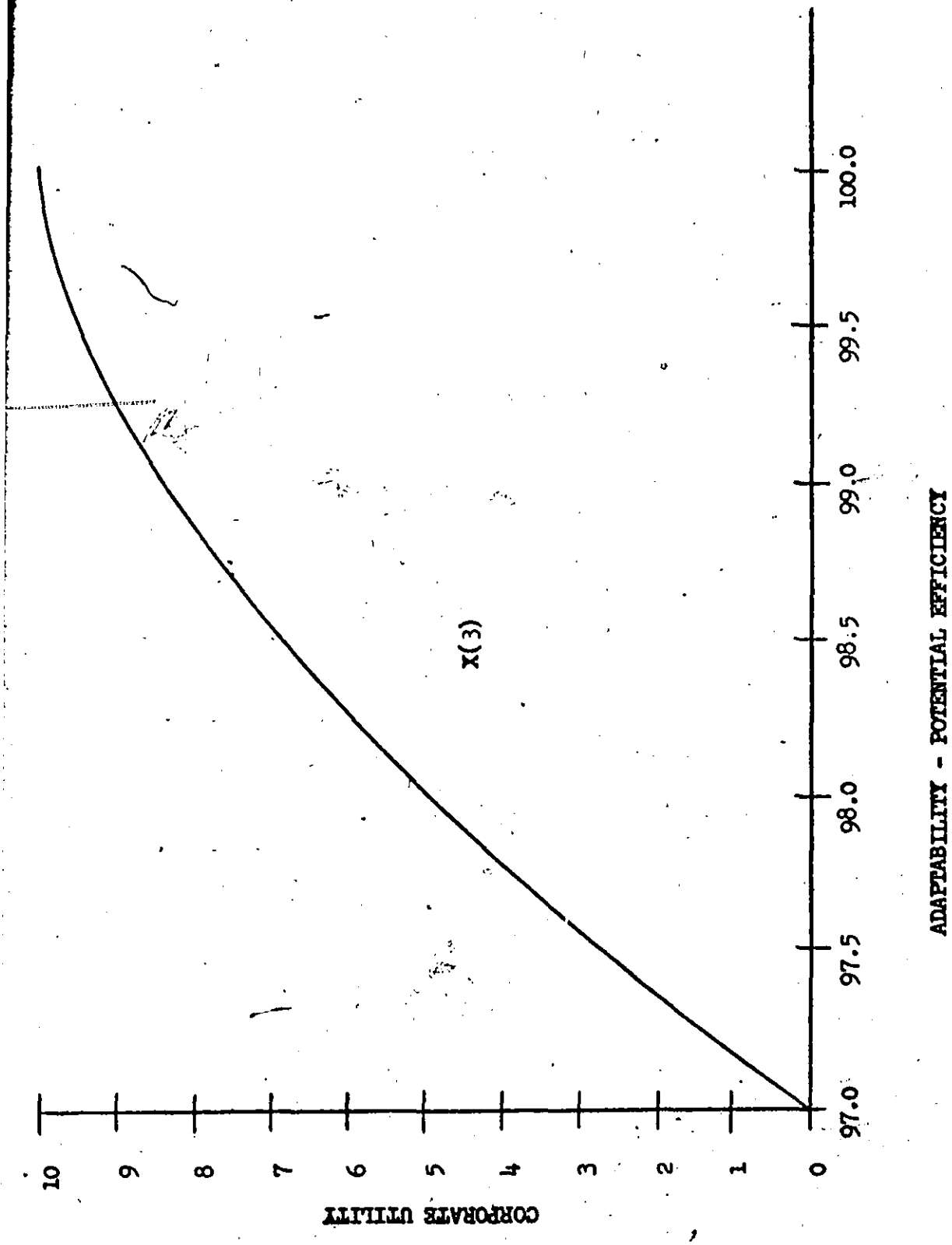
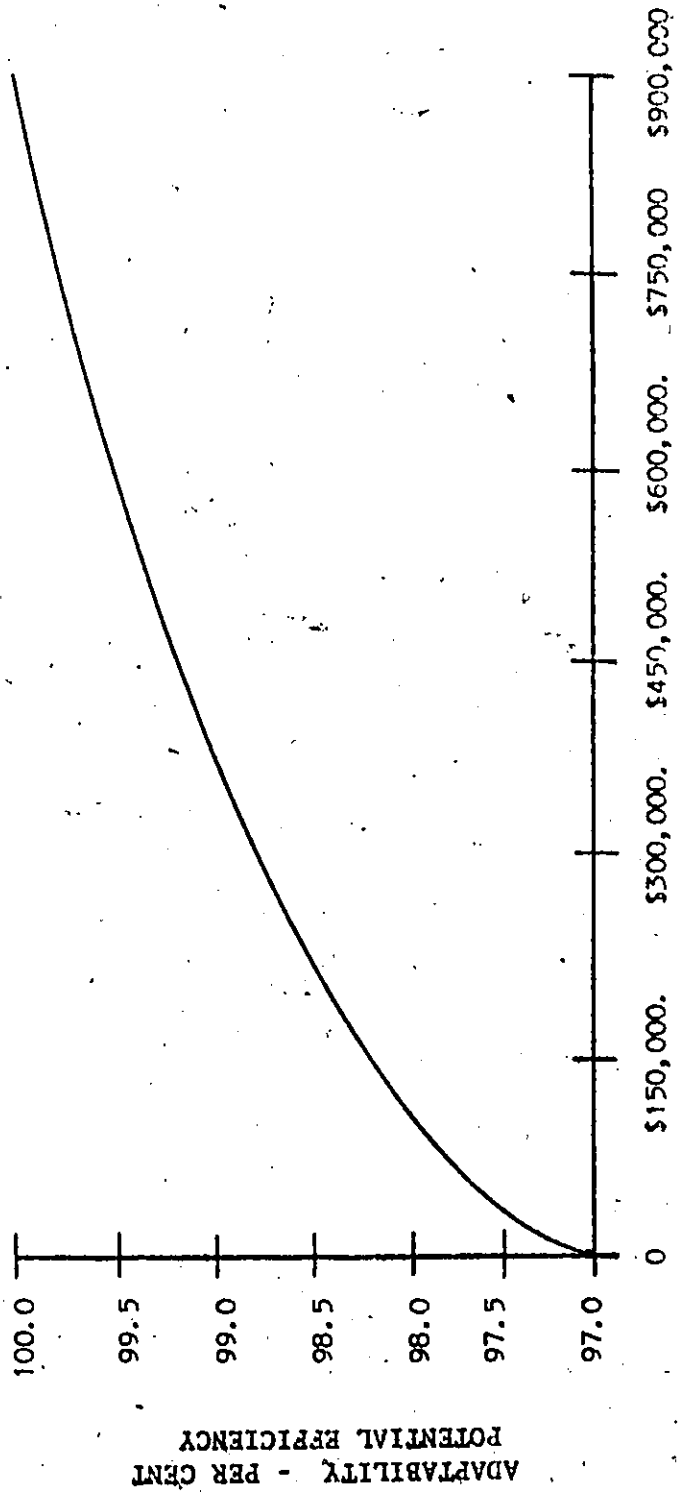

CORPORATE UTILITY
0
1
2
3
4
5
6
7
8
9
10
97.0
97.5
98.0
98.5
99.0
99.5
100.0
ADAPTABILITY - POTENTIAL EFFICIENCY
X(3)

Figure 7


ADAPTABILITY - PER CENT POTENTIAL EFFICIENCY
100.0
99.5
99.0
98.5
98.0
97.5
97.0
0
$150,000.
$300,000.
$450,000.
$600,000.
$750,000
$900,000
CAPITAL COST

Utility Curves - Variable X(4) - Noise Reduction

The noise reduction considered for the emission control unit ranged up to 15 decibels on the A scale. Logically then, 15 dB(A) will correspond to a utility value of 10; 0dB(A) will correspond to a utility value of 0. Past experience has shown that a 5dB(A) to 10dB(A) reduction has the effect of preventing noise complaints from the community.

The first 10dB(A) drop will have a rapidly increasing utility value, while additional dB(A) reductions act only as extra insurance against complaints, and have a corresponding smaller contribution to utility. The utility curve resembles that of variable X(3).

The costs necessary to effect noise reductions rise exponentially as shown by the capital cost curve based on Table 3.

Table 3

Noise Level Reduction	Item Number	Method	Cost
2dba	1	larger duct, slower fan	$ 20,000.00
4dba	2	Item 1 plus exhaust duct stack silencers	$ 45,000.00
6dba	3	Item 2 plus improved acoustical siding in enclosure	$ 85,000.00
15dba	4	Item 3 plus major design refinements	$ 335,000.00

Figure 8

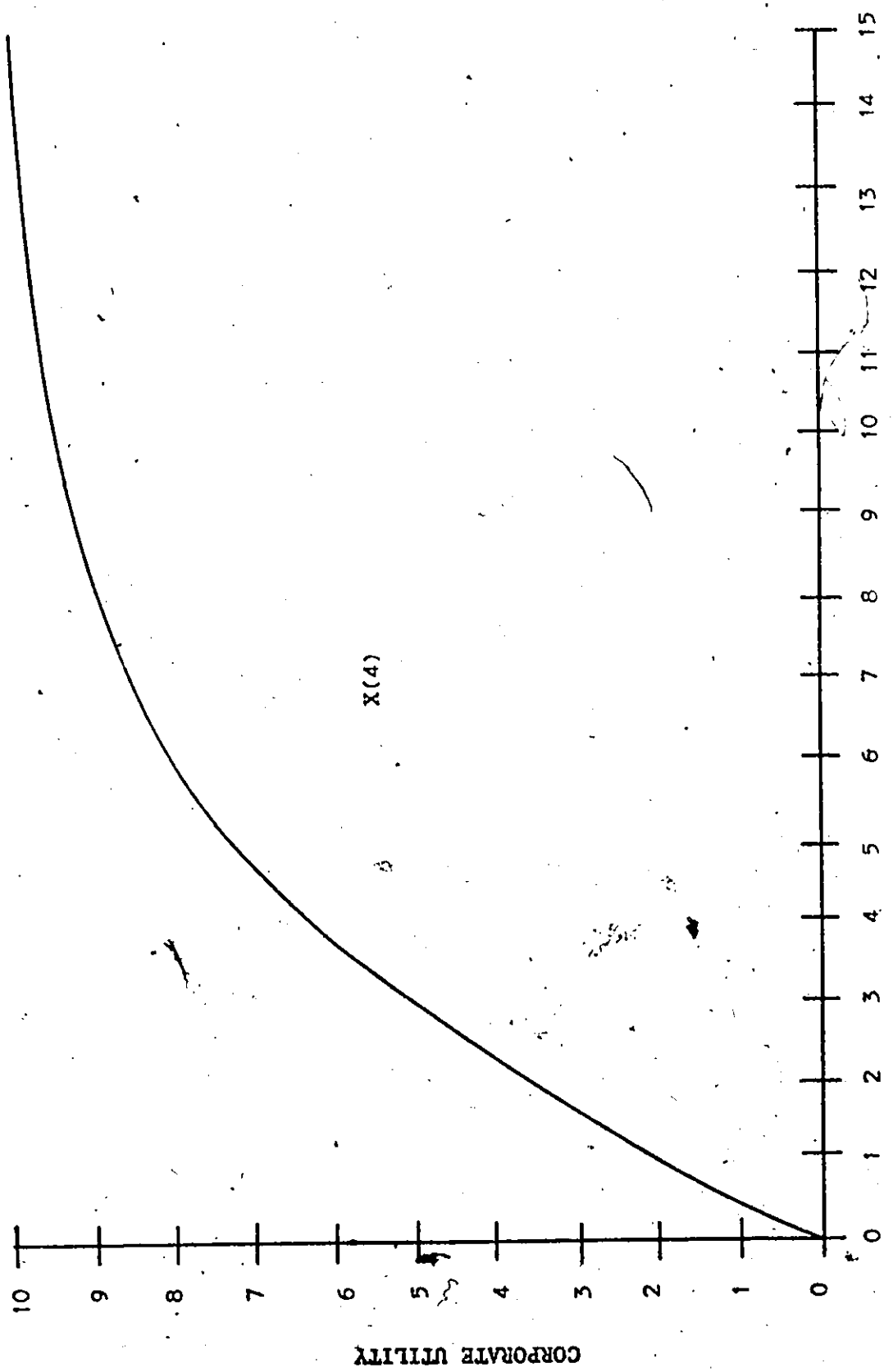
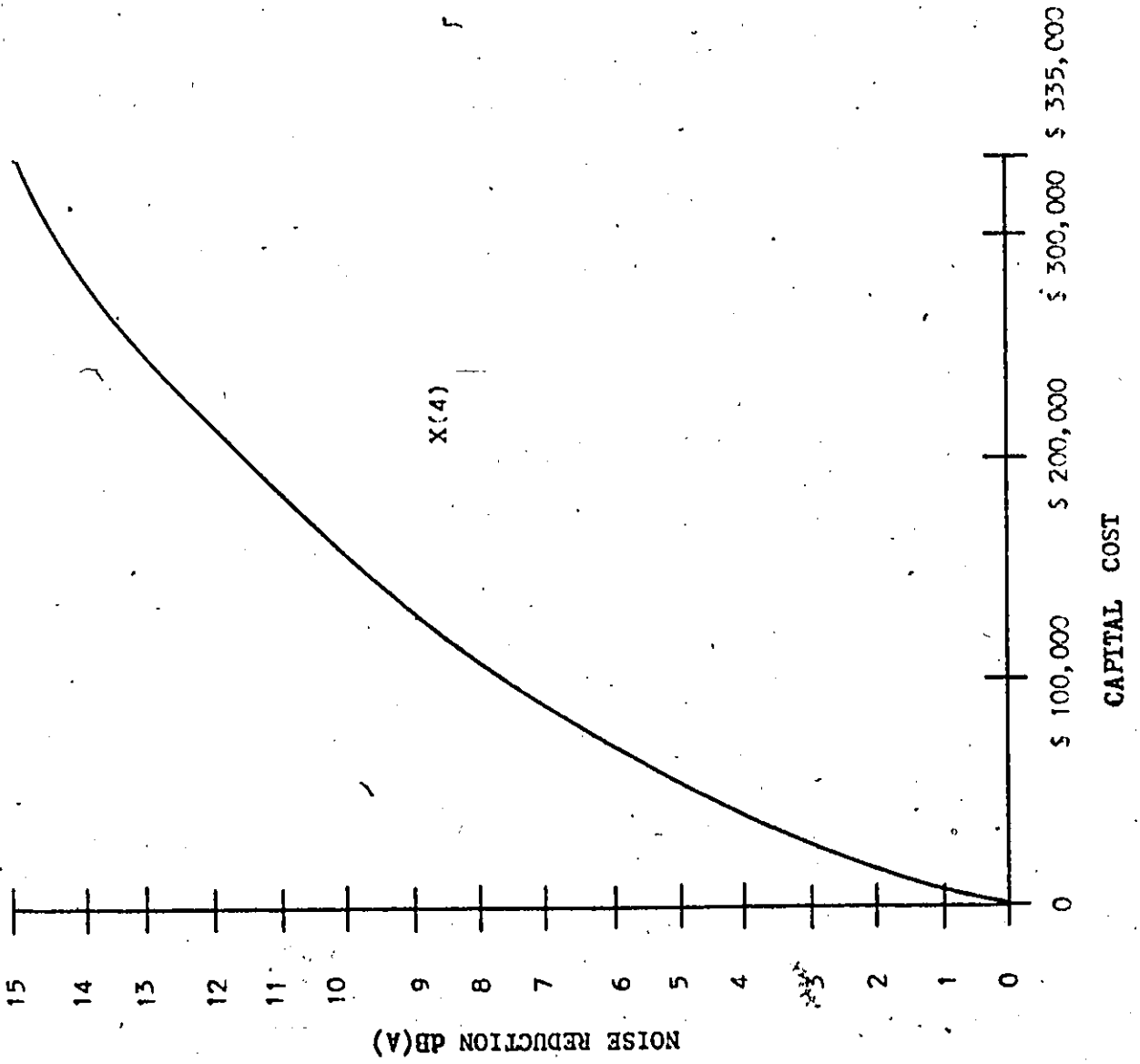

CORPORATE UTILITY
0
1
2
3
4
5
6
7
8
9
10
X(4)
NOISE REDUCTION - dB (A)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

Figure 9


NOISE REDUCTION dB(A)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
$ 100,000
$ 200,000
$ 300,000
$ 335,000
CAPITAL COST
X(4)

Utility Curve - Variable X(5) - Roof Program

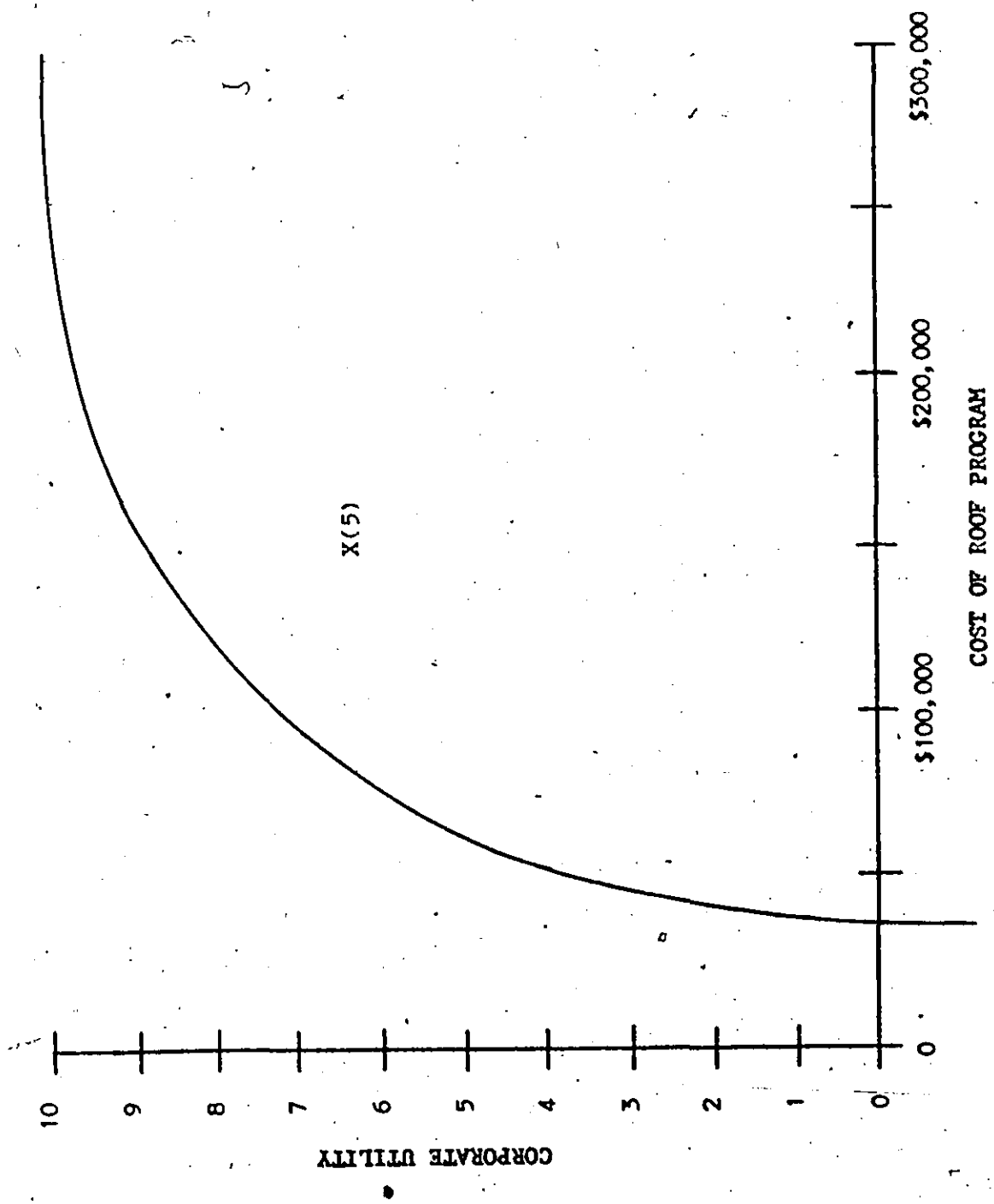
As with variable X(1), variable X(5) relates capital cost to utility, the variable was difficult to measure directly.

Note that the prevention of exhaust gases from entering the fresh air system is required by legislation. This means that any expenditure less than the required $ 40,000.00 is unacceptable and is represented by zero or negative utility. Labour union complaints in a contract negotiation year about the outside plant environments such as 1973 could force a study of the roof equipment and perhaps some modifications to improve dispersion of exhaust emissions, but it is unlikely that a costly program would be immediately undertaken for this relatively small nuisance. Table 4 is shown along with the utility curve based on this discussion.

Table 4

Item	Priority	Cost
Inlet-Exhaust Relocation	Must satisfy legislation	$ 40,000.00
Stack height changes to improve dispersion and outside air quality	To satisfy union demands	$ 10,000.00 professional study and up to $ 200,000.00 for stack changes.

Figure 10


CORPORATE UTILITY
10
9
8
7
6
5
4
3
2
1
0
$100,000
$200,000
$300,000
COST OF ROOF PROGRAM
X(5)

Utility Curves - Variable X(6) - Light and Colour

The utility curve relating to productivity increases for variable X(6) in the rotor machinery department is a simple straight line. Had the expected increase of productivity been above 5 per cent or 10 per cent, the utility curve would resemble that of X(4). An increase above 5 per cent in production would cause material handling difficulties; an increase of above 10 per cent would not be desirable since production schedules would be significantly overrun. The utility curve would of course reflect this reducing amount of utility. The expected maximum increase using light and colour is 3 per cent. This amount is desirable, to eliminate occasional overtime production work, and is well within the material handling capacity in the rotor machining area; thus the straight line curve. Table 5 is displayed here again along with the utility curve.

Since variable X(6) represents a new approach the maintenance and operating costs of the light and colour program have been included for study and are shown on the operating and maintenance cost curve. Also shown is a curve relating productivity to capital cost, necessary for the budget analysis.

Table 5.

Step	Description	Capital Cost	Operating Cost, includes maintenance
1	Raise average light level to 70 footcandles	$ 31,500.00	$ 9,500.00
2	Paint ceiling white	$ 3,000.00	$ 1,000.00
3	Paint machinery cheerful colours	$ 6,000.00	$ 600.00
4	Adopt A.N.S.I. colour code in full	$ 2,000.00	$ 200.00
5	Housekeeping improvement (light & colour improvement to employee eating and working facilities	$ 2,500.00	$ 250.00

The steps in the light and colour program are listed in order of expected importance, and will be carried out sequentially for a given budget allocation. Of prime importance is raising the local light level from an average of 20 to 40 footcandles to 70 footcandles, represented by step one. The higher light level is more in line with recommendations of the Illuminating Engineering Society (17).

The impact of the light and colour program was investigated for effects on housekeeping, safety and labour relations, three other dependent variables affected by the capital cost allocations for independent variable X(6).

If all steps are carried out, the rotor area would have a clean, cheerful atmosphere, desirable for General Motors open house to the public, or tours by visiting corporation officials. A curve was developed to relate capital cost expenditures to contribution to housekeeping. Housekeeping level was measured from 0 to 100 per cent of possible improvement. Note that the painting not lighting facets of the program are more important for display of housekeeping.

Due to the good safety record and small number of employees in the rotor area, the effect of better lighting to reduce injuries would be minimal, estimated at 5 per cent. The return on investment in terms of lost man-hours of work is negligible. However, General Motors is proud of its safety record and expenditures for variable X(6) would reduce some possibilities of injury due to light and colour. Refer to the safety curve.

There have not been complaints from the labour union about general lighting levels; the only significant step to improve relations would be step 5, relating to housekeeping.

The improvement in labour relations is estimated in reduced number of complaints formal or informal, to be expected by the foreman in the area, concerning working conditions, and is estimated not to exceed 10 per cent.

This information is reflected on the labour relations utility curve. The usefulness of the many graphs based on the variables are discussed under conclusions. All utility curves related to variable X(6) will be straight lines.

Figure 11

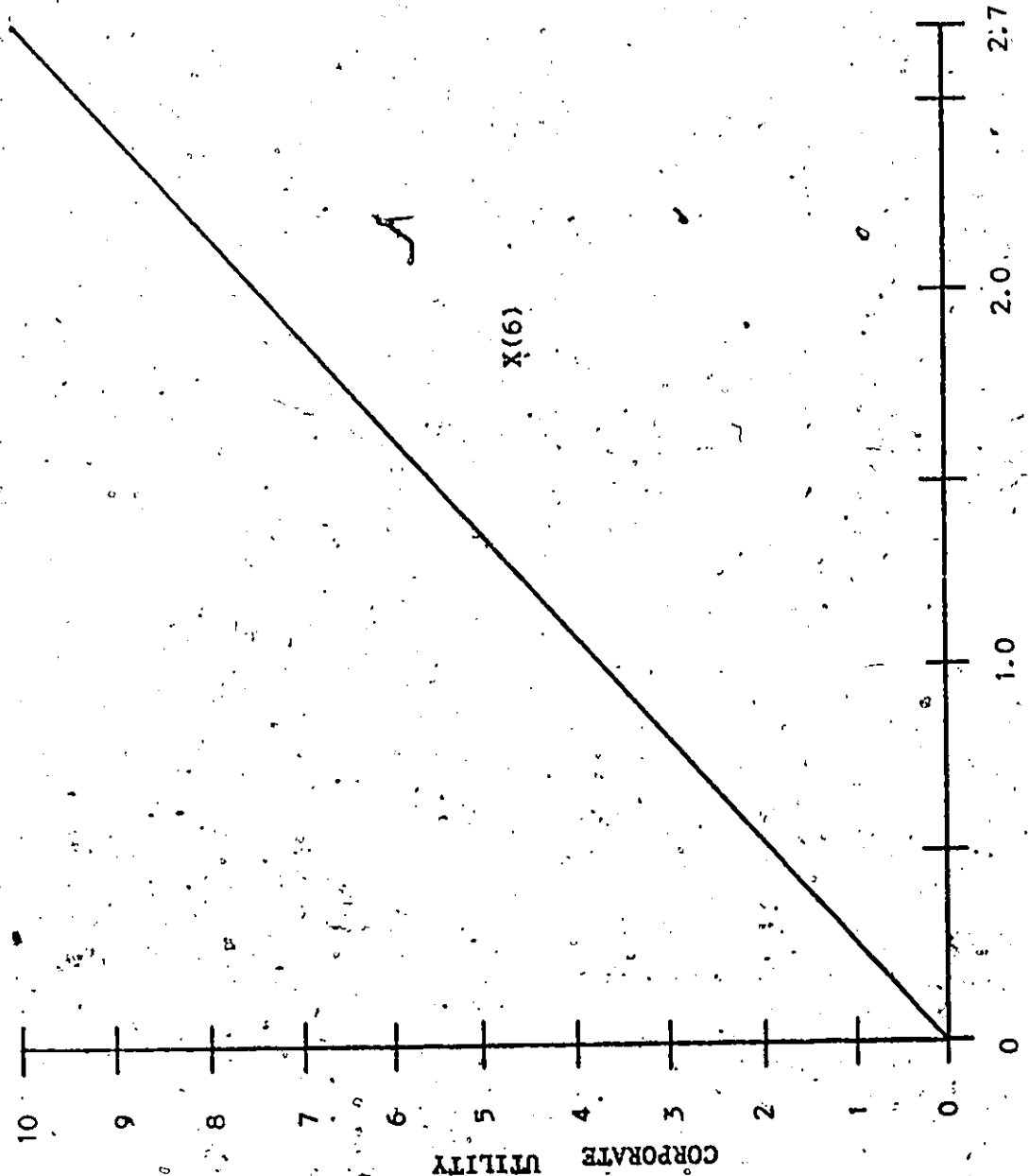

CORPORATE UTILITY
10
9
8
7
6
5
4
3
2
1
0
X(6)
0
1.0
2.0
2.7
PER CENT PRODUCTIVITY INCREASE

Figure 12

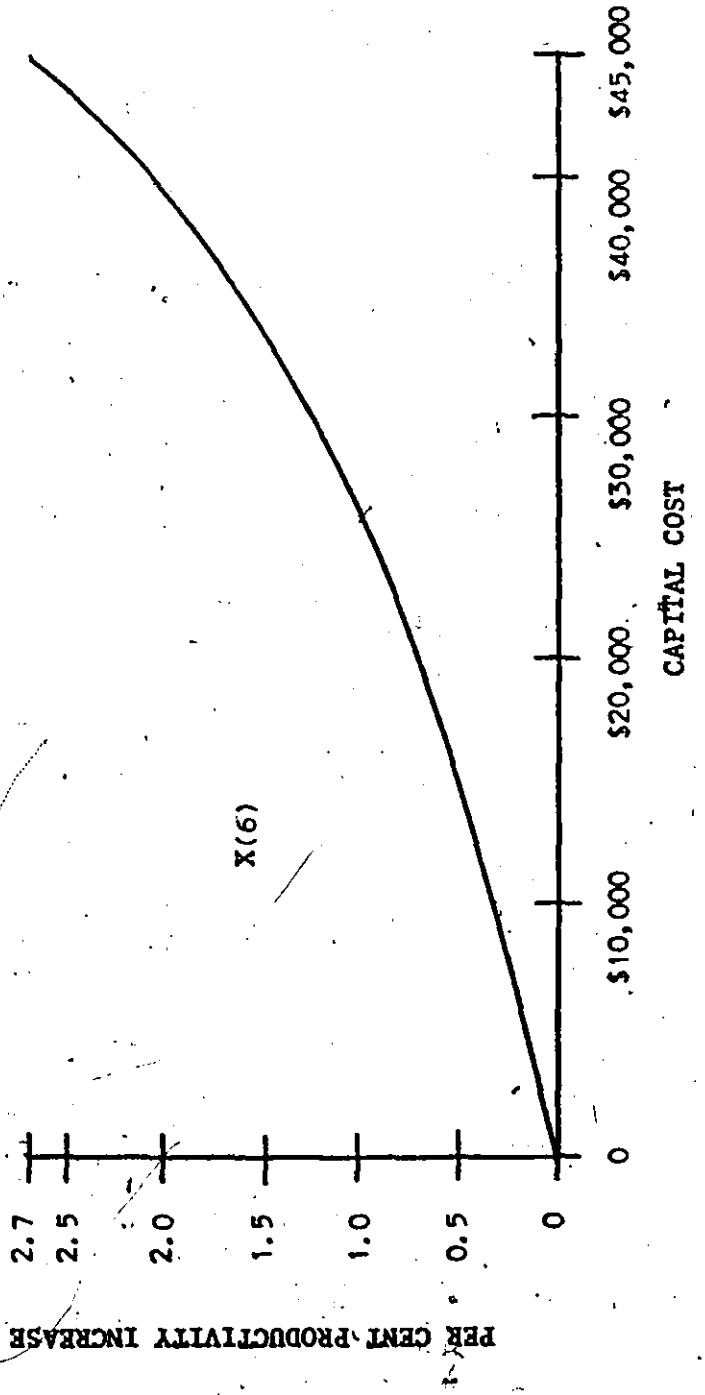

PER CENT PRODUCTIVITY INCREASE
2.7
2.5
2.0
1.5
1.0
0.5
0
0
$10,000
$20,000
$30,000
$40,000
$45,000
CAPITAL COST
X(6)

Figure 13

X(6)
CORPORATE UTILITY
0
1
2
3
4
5
6
7
8
9
10
PER CENT REDUCTION IN LABOUR COMPLAINTS
OR PERCENT IMPROVEMENT IN LABOUR RELATIONS

Figure 14

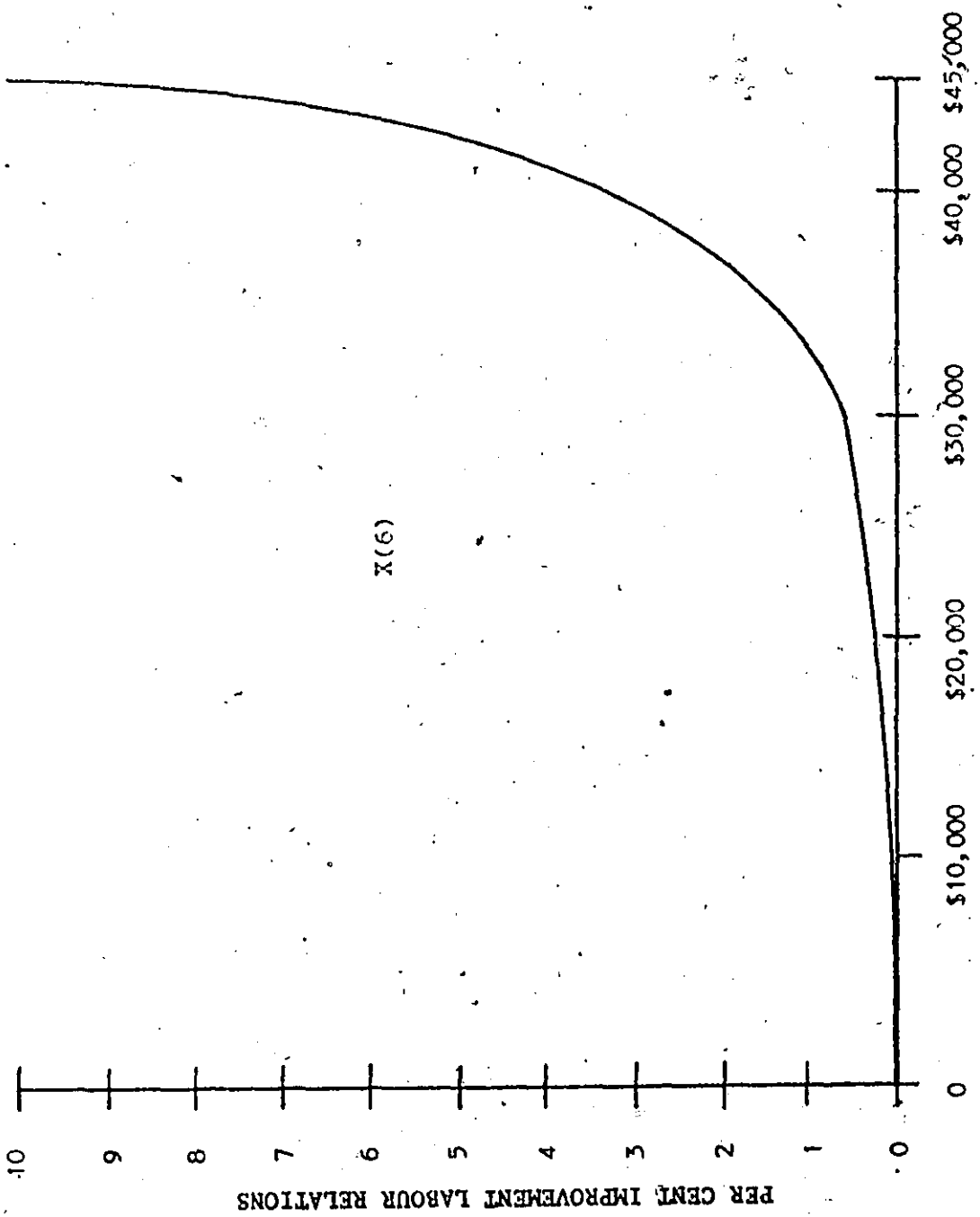

X(6)
CAPITAL COST
$10,000
$20,000
$30,000
$40,000
$45,000
0
PER CENT IMPROVEMENT LABOUR RELATIONS
10
9
8
7
6
5
4
3
2
1
0

Figure 15

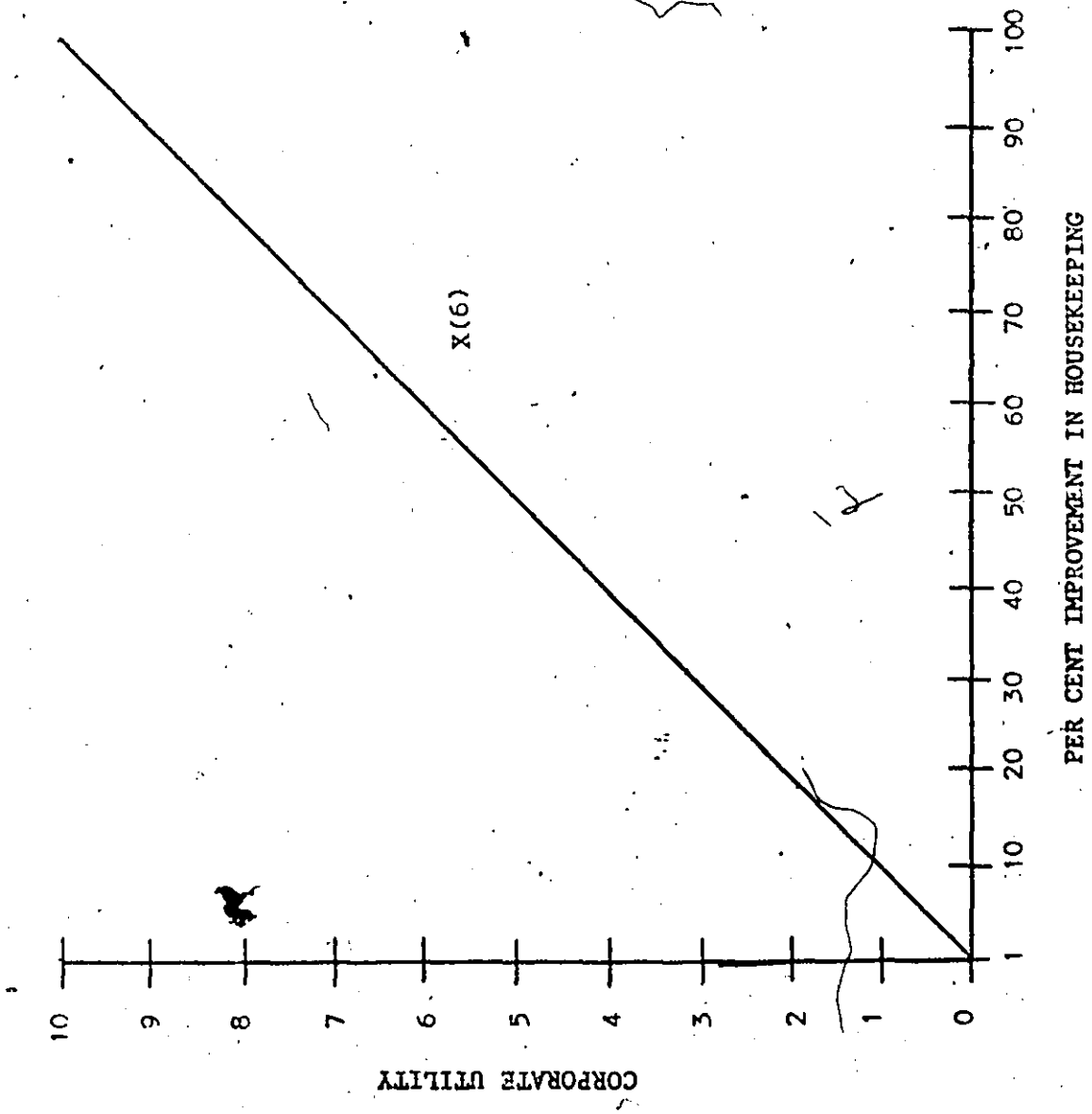

CORPORATE UTILITY
0
1
2
3
4
5
6
7
8
9
10
X(6)
1
10
20
30
40
50
60
70
80
90
100
PER CENT IMPROVEMENT IN HOUSEKEEPING

Figure 16

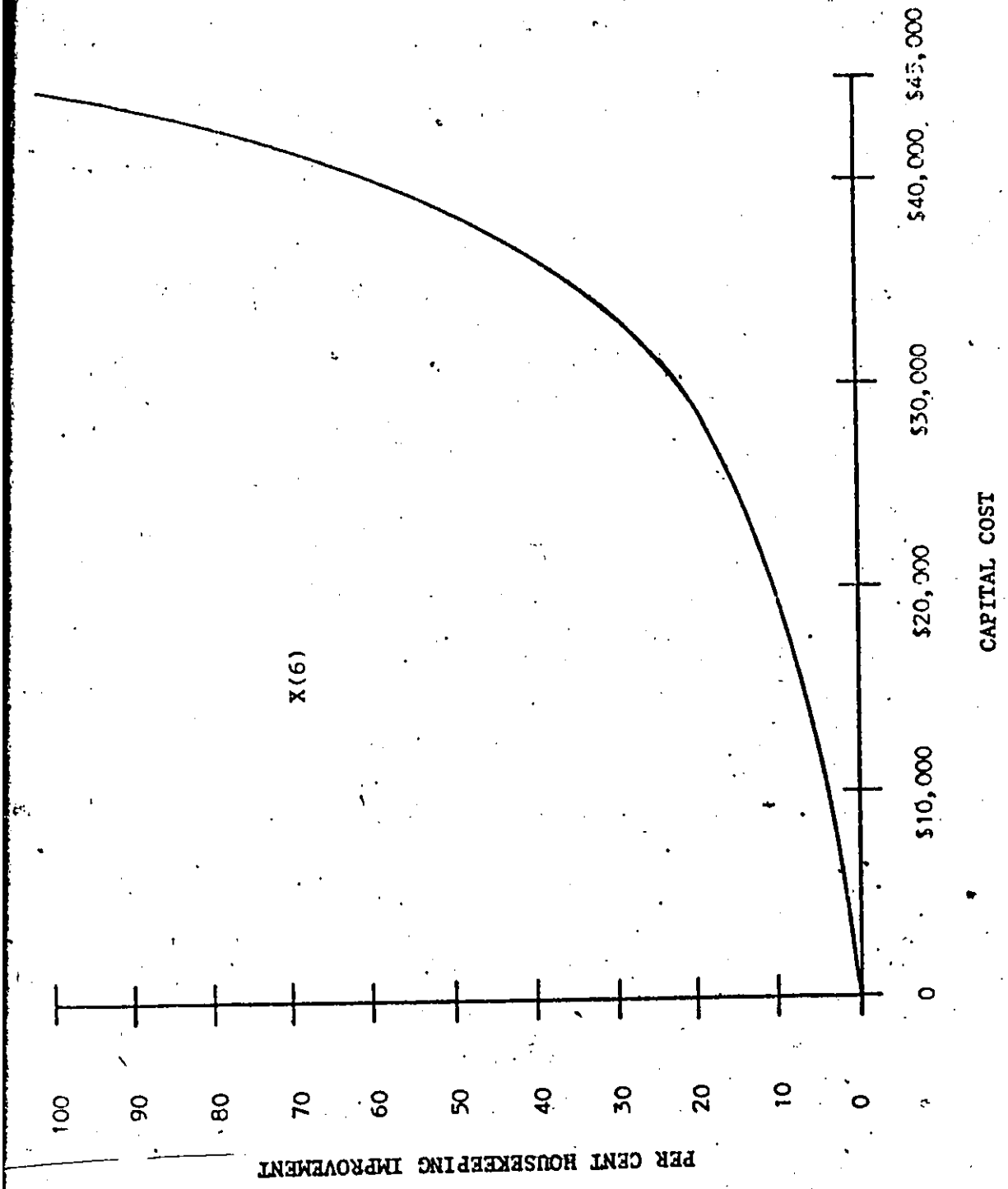

PER CENT HOUSEKEEPING IMPROVEMENT
100
90
80
70
60
50
40
30
20
10
0
0
$10,000
$20,000
$30,000
$40,000
$45,000
CAPITAL COST
X(6)

Figure 17

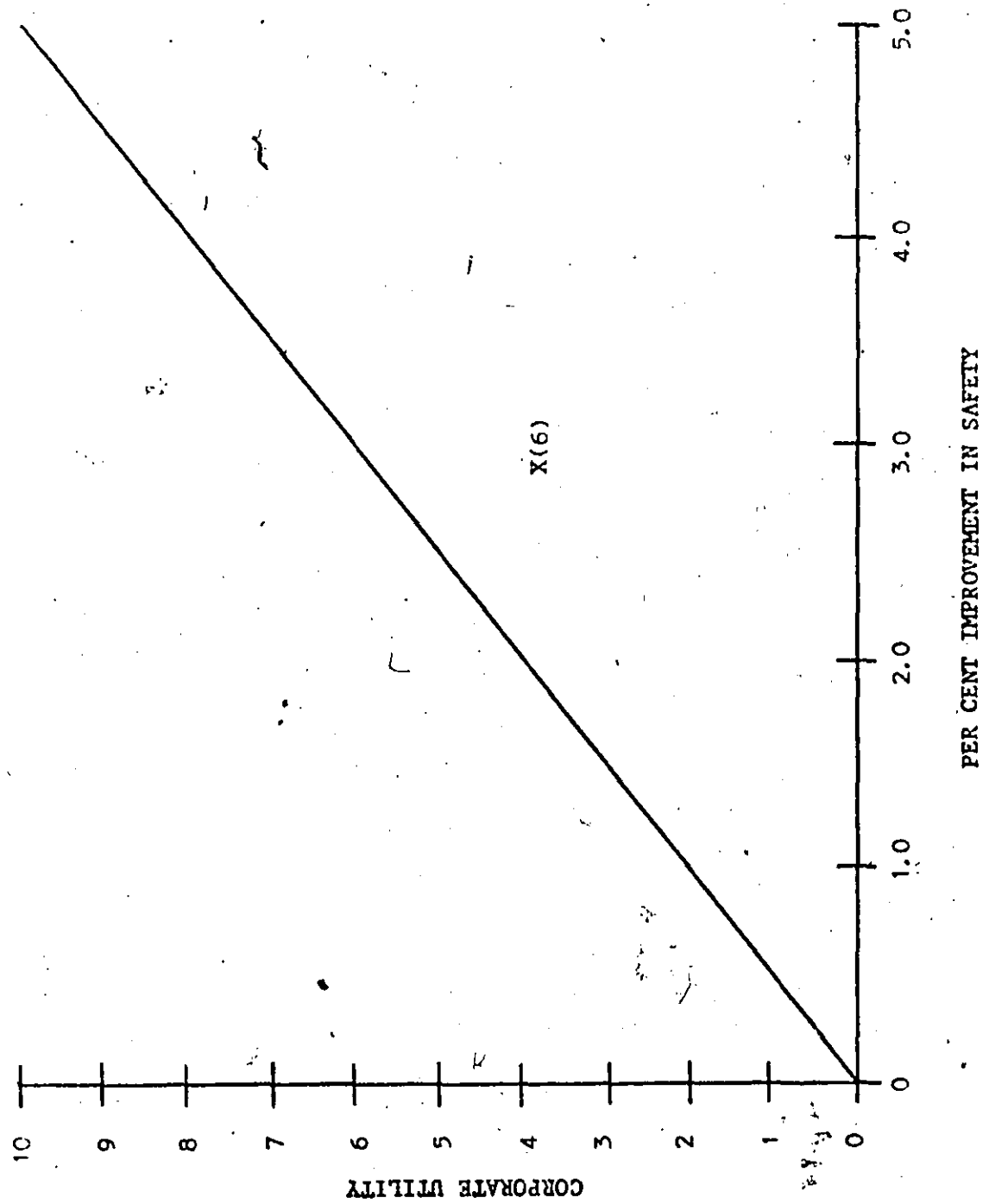

CORPORATE UTILITY
10
9
8
7
6
5
4
3
2
1
0
X(6)
0
1.0
2.0
3.0
4.0
5.0
PER CENT IMPROVEMENT IN SAFETY

Figure 18

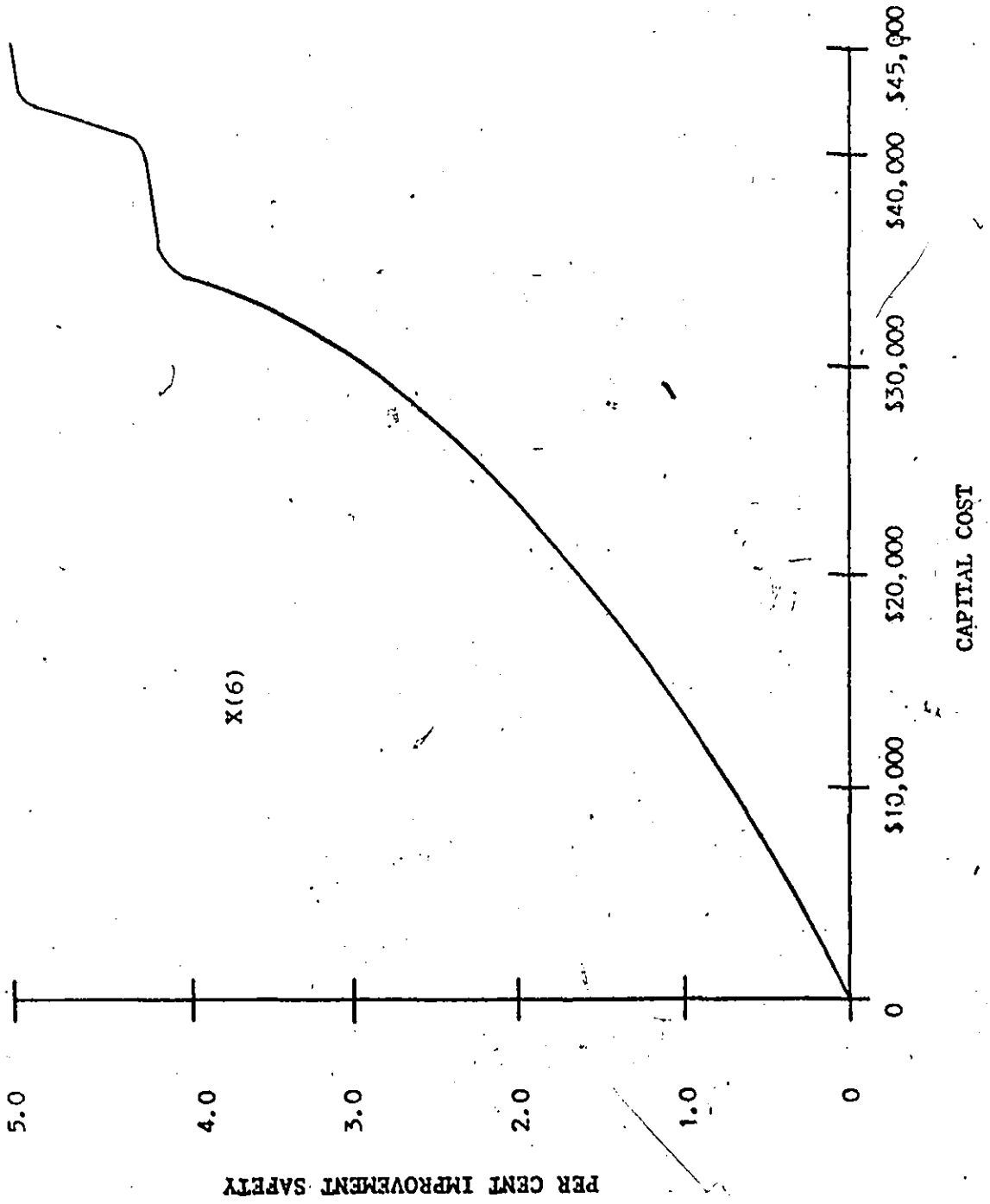
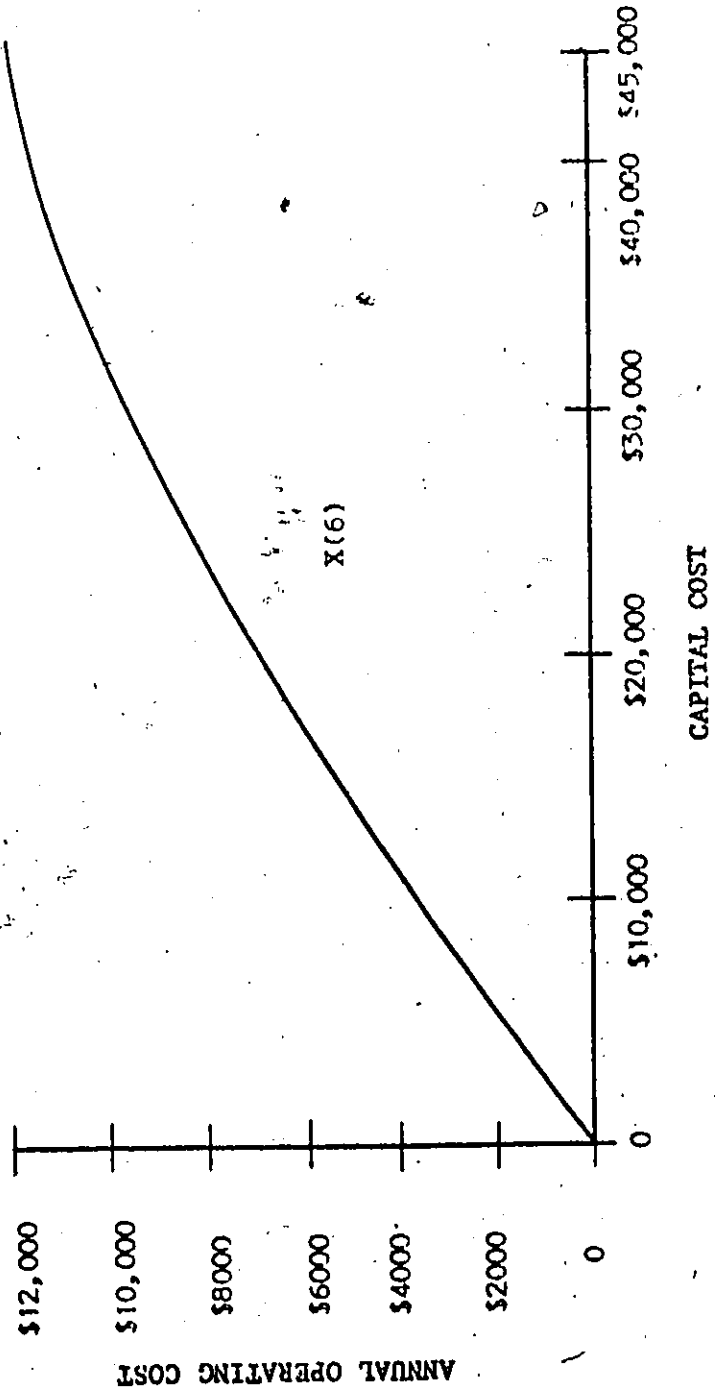

PER CENT IMPROVEMENT SAFETY
5.0
4.0
3.0
2.0
1.0
0
0
$10,000
$20,000
$30,000
$40,000
$45,000
CAPITAL COST
X(6)

Figure 19


ANNUAL OPERATING COST
$12,000
$10,000
$8000
$6000
$4000
$2000
0
0
$10,000
$20,000
$30,000
$40,000
$45,000
CAPITAL COST
X(6)

V. WEIGHTING OF UTILITY CURVES

Further considerations of utility value must be studied, in order to properly combine the contribution of utility made by each variable. Various techniques are available for aggregating utilities of several variables, including Keeney's approach (24), Woodson's method (25), Harrington's Desirability Function (26), the Ranking Array Technique (27), and the Zero-max Technique (3). To be consistent with the method used in sketching utility curves, the Zero-max technique was chosen to aggregate utilities.

Of importance with any technique is the means used to weight the utility contribution of each variable. The method used in the Zero-max Technique involves selection of scaling factors to represent the relative desirability obtained from each variable. The selection is accomplished as follows :

1. Consider each plant design variable or environmental characteristic at its maximum value; that is, the value represented by 10 on the appropriate utility curve.

2. Rank these values in order of desirability or importance.

3. Give the highest ranked value a rating of 10.

4. Give the values of the other variables a rating which reflects their relative desirability compared to this most desirable variable.

For example, if maximum noise reduction is ranked 10, and maximum good will is considered 30 per cent as desirable as maximum noise reduction, then good will is given a rating of 3.

The selection of accurate scaling factors is,along with sketching utility curves, the most difficult part of the procedure used for the budget allocation problem. As previously discussed in Chapter II of the thesis, several members of the senior staff responsible for budget development should develop scaling factors. These factors can then be aggregated to form one set of scaling factors, representing combined desirability of the variables, as seen by engineering, production, and industrial relations members of the staff. The DELPHI method (39) can be used to aggregate the scaling factors.

Once the scaling is complete, and the ordinates of the utility curves are adjusted to their new values, another check can be made. One can select the value of each variable corresponding to an arbitrary point on the utility curves that corresponds to, say 5 units of utility. If the weighting is accurate, the desirability of these values will be equal.

Harrington (26) proposed that scaling factors would be unnecessary if his method for developing utility functions was used. His approach may be difficult to use, however, if one is is not familiar with value theory and utility functions. Additional approaches to weighting are presented by Klee (37), and Turban and Metersky (38).

Reasonable scaling factors, chosen by the author, are included in Table 6, based on the method described earlier for use with the Zero-max Technique (3).

Table 6

Independent Variable	Dependent Variable	Rating	Ordinates of points on applicable utility curves to be multiplied by
X(1)	Good Will	3	0.3
X(2)	Operating Cost Savings-Dust Collector	5	0.5
X(3)	Adaptability to future legislation	7	0.7
X(4)	Noise Reduction	10	1.0
X(5)	General Roof Exhaust - emission	8	0.8
X(6)	Productivity	10	1.0
X(6)	Housekeeping	2	0.2
X(6)	Labour Relations	2	0.2
X(6)	Safety	1	0.1

VI. CONSTRAINTS USED ON THE VARIABLES

The optimization procedure that will maximize the combined utility of the variables and will determine capital expenditures, is capable of analyzing more factors than are associated with the previously discussed utility curves. Although the prime consideration is analysis of subjective variables, one may also consider such items as, return on investment, operating costs, time value of money invested, and probability. That is, many of the realistic inputs required for a logical development of a capital budget can be incorporated into the optimization procedure.

These inputs are entered into the optimization computor program as constraints ;

Constraints Common to all Variables

A review of optimization (3) and of the optimization subroutines used (4) may be appropriate.

The first twelve inequality-constraints used, simply restrict the six independent variables to a feasible range of expenditures, as defined by utility functions. These constraints are entered in Subroutine CONST, part of the main computer program. All inequality constraints are coded as PHI in the program. The constraints are listed:

PHI (1) = X(1) ≥ 0

PHI (2) = 500000.0 - X(1) ≥ 0

PHI (3) = X(2) - 50000.0 ≥ 0

PHI (4) = 60000.0 - X(2) ≥ 0

PHI (5) = X(3) ≥ 0

PHI (6) = 800000.0 - X(3) ≥ 0

PHI (7) = X(4) ≥ 0

PHI (8) = 335000. - X(4) ≥ 0

PHI (9) = X(5) ≥ 0

PHI (10) = 300000 - X(5) ≥ 0

PHI (11) = X(6) ≥ 0

PHI (12) = 45000.0 - X(6) ≥ 0

Additional Inequality Constraint for Variable X(2)

Constraint PHI (13) was added to ensure that any operating cost savings resultant from variable X(2) are greater than any capital expenditure beyond $ 50,000.00 on the dust collector.

Development of constraint PHI (13) considers the time value of money. Reference is made to this topic in Appendix F. The capital cost, if in excess of $ 50,000.00, is converted to an annual expenditure for comparison with annual operating cost savings. Expected life of the dust collector is 10 years. The conversion included possible earnings of excess capital cost if it had been invested at 9 per cent per annum.

R = Equivalent annual cost of capital exceeding $ 50,000.00 or periodic payment

P = Capital expenditures in excess of $ 50,000.00

i = Interest rate, if excess capital was invested

n = Life of dust collector years

$$R = P \cdot \frac{i(1 + i)^n}{(1 + i)^n - 1}$$

In the computer program R is represented as COST. The operating cost savings, variable X(2) are coded as SAVE. As long as SAVE, during the 10 year lifetime of the dust collector, is greater than COST, the selection of the dust collector is acceptable.

SAVE = COCS x 10 = total savings in 10 years

BEN = SAVE - COST

and the constraint reads

PHI (13) = BEN 0

Additional Constraint for Variable X(3)

If there are no foreseeable plans for more stringent legislation concerning cupola emission control systems, there is no need for variable X(3). A constraining statement was included to require a minimum probability of more stringent legislation before variable X(3) can be included in the budget. If the probability of future legislation drops below a lower limit, set at 0.5, the only output from the program will be a statement suggesting the program be re-run without variable X(3). Note that the author did not choose to develop any sophisticated means of predicting probability. The intent of the author was to introduce optimization as a simple tool for management. As the tool becomes more familiar to people in industry, the more powerful aspects of optimization including probability prediction can be employed.

Additional Inequality Constraint for Variable X(6)

Because of the nature of the light and colour program, it is logical to constrain the optimum capital expenditure to the region where the return on investment is acceptable.

CPROD = per cent expected increase in productivity

The current value of increased production was estimated at $ 15,000.00 per year for every 1 per cent gain. The initial annual return in dollars is XRET,

where XRET = CPROD X 15,000.

The life of the light and colour program was estimated at 10 years. The total dollar return after 10 years based on a % per cent annual increase due to inflation is XTOT.

$$XTOT = \sum_{j=0}^{n-1} XRET\ (1.0+i)^j$$

where R = XRET

Sn = XTOT

n = 10 years

i = 5 per cent

The initial capital cost of the light and colour program is the value of variable X(6). The initial annual operating cost is ZOP. The total cost over a 10 year period is X(6) plus ZOP for 10 years, based on a 5 per cent annual increase in operating and maintenance costs, and is coded XCOST. **Note, ZOP increase was not compounded, an unrealistic event.**

$$XCOST = X(6) + ZOP \times \frac{(1.0 + 0.05)^5 - 1}{0.5}$$

This equation is based on the equation

$$SN = R \frac{(1 + i)^n - 1}{i} + \text{a constant}$$

where Sn = XCOST constant = X(6)

R = ZOP

n = 10 years

i = 5 per cent 0.05

The constraint PHI (14) ensures that the lifetime return on the light and colour program will be greater than expenditure

PHI (14) = XTOT - XCOST

As well as requiring a monetary return on investment before an optimum solution can be found, a constraining statement was added to void the inclusion of variable X(6) in the budget, if the return on investment, in years, exceeds five years, based on

$$\text{YEARS} = \frac{X(6)}{\text{XRET}}$$

The value of constraint PHI (14) becomes evident when one considers the current energy shortage. Note that the main operating cost of the light and colour program is the cost of electrical energy. If the energy costs increase at a faster rate than the increase in return, by as little as 5 per cent per year, PHI (14) becomes economically unattractive, a development not obvious when basing return on investment solely on a calculation such as YEARS.

Additional Inequality Constraints Affecting all Variables

The total capital expenditure for all items is coded COSTOT. Constraints PHI (15) and PHI (16) limit the total amount of money available for the portion of the engineering budget developed in this thesis.

PHI (15) = COSTOT - proposed budget amount ≥ 0

PHI (16) = (proposed budget - less \$100) - COSTOT ≥ 0

VII. OPTIMIZATION EXPRESSION

The six variables to be optimized have been well documented and analyzed. The final requirement of the optimization procedure is an optimization expression that will maximize or minimize utility.

Independent Variable	Coded symbol for Utility Value Based on Related Dependent Variable
X(1)	ZPR
X(2)	ZOCS
X(3)	ZADAPT
X(4)	ZDB
X(5)	ZROOF
X(6)	ZPROD
	ZLAB
	ZHOUSE
	ZSAFE

There are two approaches used in an optimization expression. Both were chosen for their simplicity.

The first is to maximize the total available utility U, where

U = ZPR + ZOCS + ZADAPT + ZDB + ZROOF + ZPROD + ZLAB + ZHOUSE + ZSAFE = maximum (3)

or, $U = \sum U_j$ = maximum, where U_j = utility of a variable.

A second approach used involved the concept of inverted utility. "It is quite possible that man's intuitive intellect minimizes combined undesirability rather than maximizing combined desirability while optimizing." (3, p.199). Rather than maximizing the utilities of the six variables, the reciprocal of the utilities are used and the undesirability of the variables is minimized; undesirability is U_j^{-1}

total undesirability is $N^{-1} = \sum U_j^{-1}$ or,

$$\frac{1}{N} = \frac{1}{ZPR} + \frac{1}{ZOCS} + \frac{1}{ZADAPT} + \frac{1}{ZDB} + \frac{1}{ZROOF} + \frac{1}{ZPROD} + \frac{1}{ZLAB} + \frac{1}{ZSAFE} + \frac{1}{ZHOUSE}$$

$$\text{or } N = \frac{1}{\frac{1}{ZPR} + \frac{1}{ZOCS} + \frac{1}{ZADAPT} + \frac{1}{ZDB} + \frac{1}{ZROOF} + \frac{1}{ZPROD} + \frac{1}{ZLAB} + \frac{1}{ZSAFE} + \frac{1}{ZHOUSE}}$$

Both approaches are discussed under Conclusions. The optimum points on the utility curve of each variable will determine the budget allocation for that variable. Other approaches that can be used to formulate the optimization expression include: combining utilities in a geometric mean, having ranked all utility curves from zero to one (26); and optimizing each variable in order of importance, adding in each step a constraint restricting the value of previously optimized variables (21). The last method does not necessarily require utility values. One may also consider using the additive inverse of utility values to minimize disutility where,

T = total disutility

U_j = utility value of each variable

$U_j max - U_j$ = disutility for each variable

The optimization expression would minimize disutility,

$$T = \sum (U_j max - U_j) = \text{minimum}$$

The equation can be simplified to produce an interesting result,

$$T = \sum U_j max - \sum U_j = \text{minimum}$$

$$T = \text{constant} - \sum U_j = \text{minimum}$$

$$-T = -\text{constant} + \sum U_j = \text{maximum}$$

$$\text{constant} - T = \sum U_j = \text{maximum}$$

By definition, the constant, a sum of all maximum utility values, less T, the disutility, is equal to U, the maximum expected utility. The expression for disutility has now been reduced to the expression for utility, developed previously.

$$U = \sum U_j = \text{maximum}$$

The first two expressions were used in the computer program developed for the budget allocation problem.

VIII. COMPUTER PROGRAM DEVELOPED FOR OPTIMIZATION OF PLANT DESIGN VARIABLES

At this point we assume that management has completely defined its problems and the relative importance of various solutions and their costs. The actual optimization; that is, the selection of various locations on each curve to maximize utility value, can be handled most efficiently by employing the computer.

This program follows the basic rules set out in the OPTISEP manual published by McMaster University (4). The OPTISEP package is a collection of optimization subroutines that can be employed to use on optimization problems. The necessary organization of input requires:

Main program - includes all input data, calls the optimization subroutine, includes formal output statements; and is named program TST in this case.

Subroutine UREAL - includes development of the optimization expression.

Subroutine CONST - includes development of all inequality constraints.

In addition, Function FTABLE has been added to form data curves from the data points entered in Program TST.

Complete listings of the program developed for this thesis, and listings of subroutines called in the program are listed in Appendix D and E. Highlights of each section of the computer program will be discussed to clarify the approach used by the author. The language used is Fortran IV for use with a CDC 6400 computer at McMaster University.

Program TST - Main Program

Entered in the main program is data for all parts of the program, and is transferred to Subroutines UREAL, and CONST, with labelled COMMON CARDS.

Data defining the various utility and cost curves is entered by listing 5 to 10 co-ordinates of points on each curve. This method was chosen for its simplicity. Function FTABLE interpolates between the given points to develop the curves for use in optimization. As the understanding and use of optimization and computers in industry grows, more complex and accurate methods of entering data can be used. The author feels that any deviations from the true curves caused by interpolation do not significantly affect the results. Function FTABLE is also used to functionally relate utility directly to cost.

As well as adding descriptive output statements to clearly explain the budget allocations and optimum selection of values of the variables, the output was designed to include all utility and cost curves with a clear indication of the optimum point on each curve. The purpose, of course, is to allow plant engineering supervisors to have a clear understanding of the optimum budget, numerically, descriptively, and graphically. In this way, the impact of a proposed budgetary limit, relative weightings of variables, and constraints becomes obvious.

Subroutine PLOTPT (11), was used to generate the curves in the output, and suitable loops were designed into the program to allow identification of the optimum point and axes on each curve. PLOTPT is stored in the central memory of the CDC 6400 computer at McMaster University.

In order to keep the program as simple as possible, existing subroutines were used rather than new ones designed for this program.

A typical optimization subroutine, chosen from the OPTISEP package, is also called in TST.

Subroutine UREAL

To satisfy the sequence of operation of the program, it was necessary to list again all terms involving the variables X(1) through X(6), plus the COMMON cards. The optimization expression was also entered in this subroutine. In the example presented in Conclusions, the optimization subroutine SEEK 1 was used, which minimizes the optimization expression; therefore the expression was changed from

$$U = (ZPR + ZOCS + ZADAPT + ZDB + ZROOF + ZPROD + ZSAFE + ZHOUSE + ZLAB) = \text{maximum}$$

to

$$U = -(ZPR + ZOCS + ZADAPT + ZDB + ZROOF + ZPROD + ZSAFE + ZHOUSE + ZLAB) = \text{minimum}$$

The expression are mathematically equivalent.

Function FTABLE

Function FTABLE was called by TST, UREAL and CONST and is entered at this point. A complete listing of FTABLE is found in Appendix B explaining its ability to interpolate between given data points.

Subroutine CONST

The inequality constraints discussed in an earlier chapter are developed and entered in subroutine CONST. Constraining statements for variables X(3) and X(6) are entered in the main program TST.

The computer was run with different optimization expressions, optimization subroutines, and budget limits. Results will be discussed under Conclusions.

It may be of interest, to understand the techniques used in the computer to find the optimum values of each variable. Reference (3) contains introductory information about optimization, and Reference (4) presents the mathematical interpretation of the optimization procedure.

Much of the program could be incorporated as part of the OPTISEP package; the result would be a simpler program for industrial use. The value of this idea was recognized by the author, but was beyond the scope of this thesis.

IX. RESULTS AND ANALYSIS OF RESULTS

This chapter will be separated into two distinct sections; results, and analysis of results , concerned with optimization of capital budget allocations for a plant engineering department of General Motors of Canada Limited.

A. Results

The initial output of the computer optimization program is a simple list of optimum values of the six variables, the related values of the constraints, and the value of the optimization expression. U gives the maximum total corporate utility that can be achieved subject to the constraints,in the example used.

U = - (maximum units of utility) = minimum

The series of X(1) to X(6) gives the optimal budget allocations in dollars for each independent variable.

The series of numbers labelled PHI (1) to PHI (15) gives the value of the contraints, given the optimum values of the variables.

This portion of output is included for the benefit of those readers most interested in the operation of the OPTISEP package, and is the standard form of output from the optimization subroutines. An example follows.

OPTIMUM SOLUTION FOUND

MINIMUM U = -.31755343E+02

X(1)	=	.23000000E+06
X(2)	=	.55650000E+05
X(3)	=	.25400000E+06
X(4)	=	.21675000E+06
X(5)	=	.21500000E+06
X(6)	=	.28600000E+05

INEQUALITY CONSTRAINTS

PHI(1)	=	.23000000E+06
PHI(2)	=	.27000000E+06
PHI(3)	=	.56200000E+04
PHI(4)	=	.43500000E+04
PHI(5)	=	.25400000E+06
PHI(6)	=	.54600000E+06
PHI(7)	=	.21675000E+06
PHI(8)	=	.11825000E+06
PHI(9)	=	.21500000E+06
PHI(10)	=	.85000000E+05
PHI(11)	=	.28600000E+05
PHI(12)	=	.16400000E+05
PHI(13)	=	.54150710E+04
PHI(14)	=	.37438967E+05
PHI(15)	=	0.
PHI(16)	=	.10000000E+03

The values of the variable X(1) through X(6) were coded into a more descriptive form; related capital costs, and effects of the light and colour program were also included, in the next stage of the computer output. Results of a program using a $ 1,000,000.00 budget are shown.

BUDGET ALLOCATIONS DETERMINED BY THIS PROGRAM

TOTAL COST IN DOLLARS 1000000.0
CAPITAL COST OF LIGHT AND COLOUR PROGRAM 28600.0
ANNUAL MAINTENANCE COST,IN DOLLARS 8345.6
PER CENT OF MAXIMUM POSSIBLE IMPROVEMENT
IN HOUSEKEEPING 16.9
PER CENT REDUCTION IN LABOUR COMPLAINTS .4
PER CENT REDUCTION IN MINOR ACCIDENTS,IE,PER CENT
INCREASED SAFETY 2.5
ALLOCATION FOR PUBLIC RELATIONS 230000.0
ANNUAL OPERATING COST SAVINGS,DOLLARS 629.5
COST OF DUST COLLECTORS,MAXIMUM 55650.0
PER CENT EFFICIENCY ATTAINABLE BY EMISSIONCONTROL
EQUIPMENT 98.7
COST OF PROVISION FOR FUTURE EFFICIENCY LEVEL 254000.0
DROP IN NOISE LEVEL 11.3
COST OF NOISE REDUCTION,DOLLARS 216750.0
ALLOCATION FOR ROOF IMPROVEMENT,DOLLARS 215000.0
OPTIMUM PRODUCTIVITY OF LIGHT AND COLOUR PROGRAM
EXPRESSED IN PER CENT .9
TOTAL 10 YEAR RETURN,LIGHT AND COLOUR PROGRAM 171009.0
RETURN ON INVESTMENT IN YEARS
FROM LIGHT AND COLOUR PROGRAM 2.7
USE CURVES PROVIDED TO ROUND OFF BUDGET ALLOCATIONS
IF REQUIRED

The last portion of the output graphically displays the optimum points on utility and cost curves. A typical output will contain a series of such graphs. Although computer graphics are available to produce more elegant line graphs, the author chose to use point graphs, since they do not require any additional equipment besides the input-output terminal.

The economic advantage of point graphs is attractive when considering industrial applications.

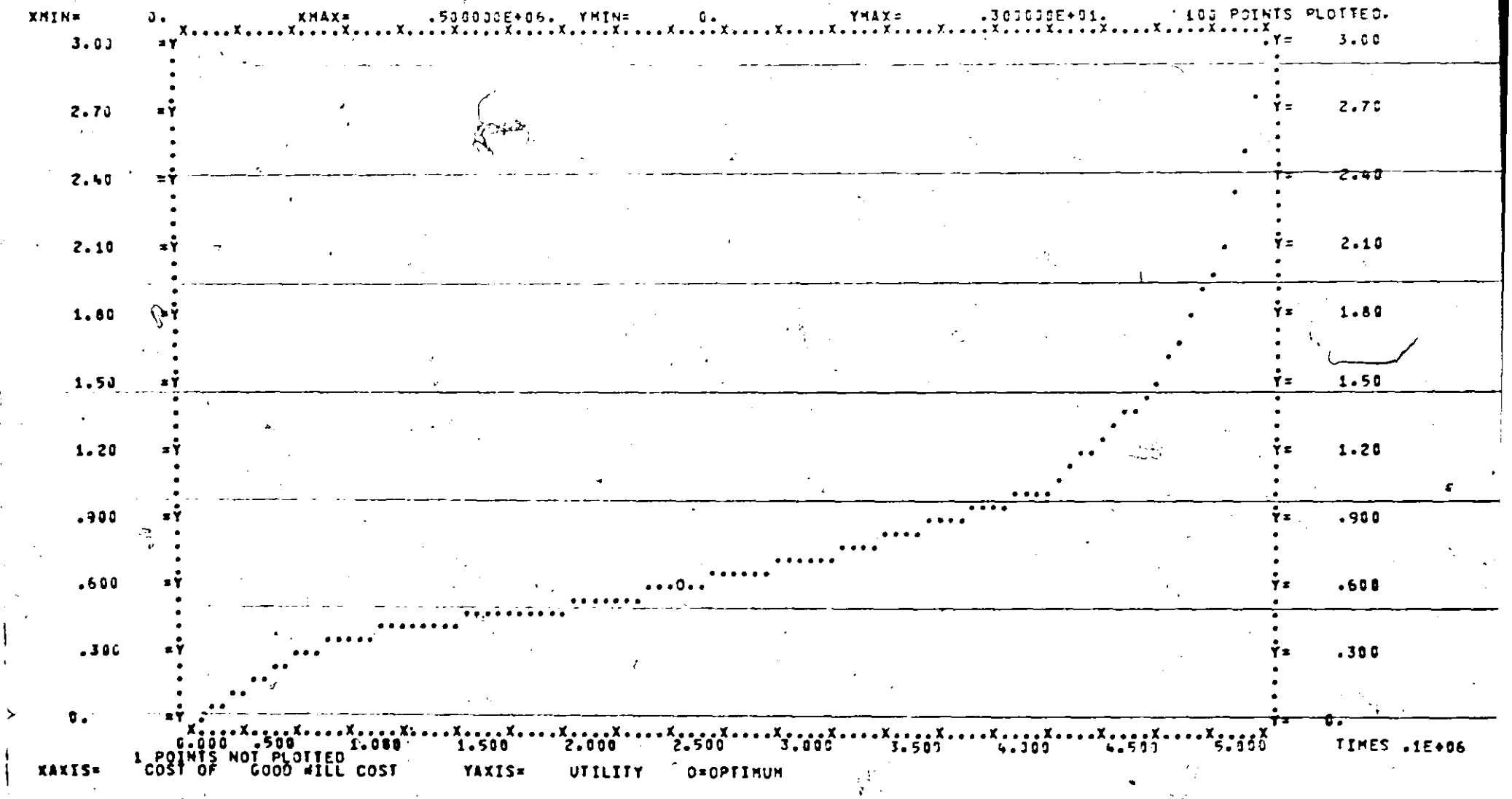


Figure 3 Variable X(1): Cost of Good Will and Utility

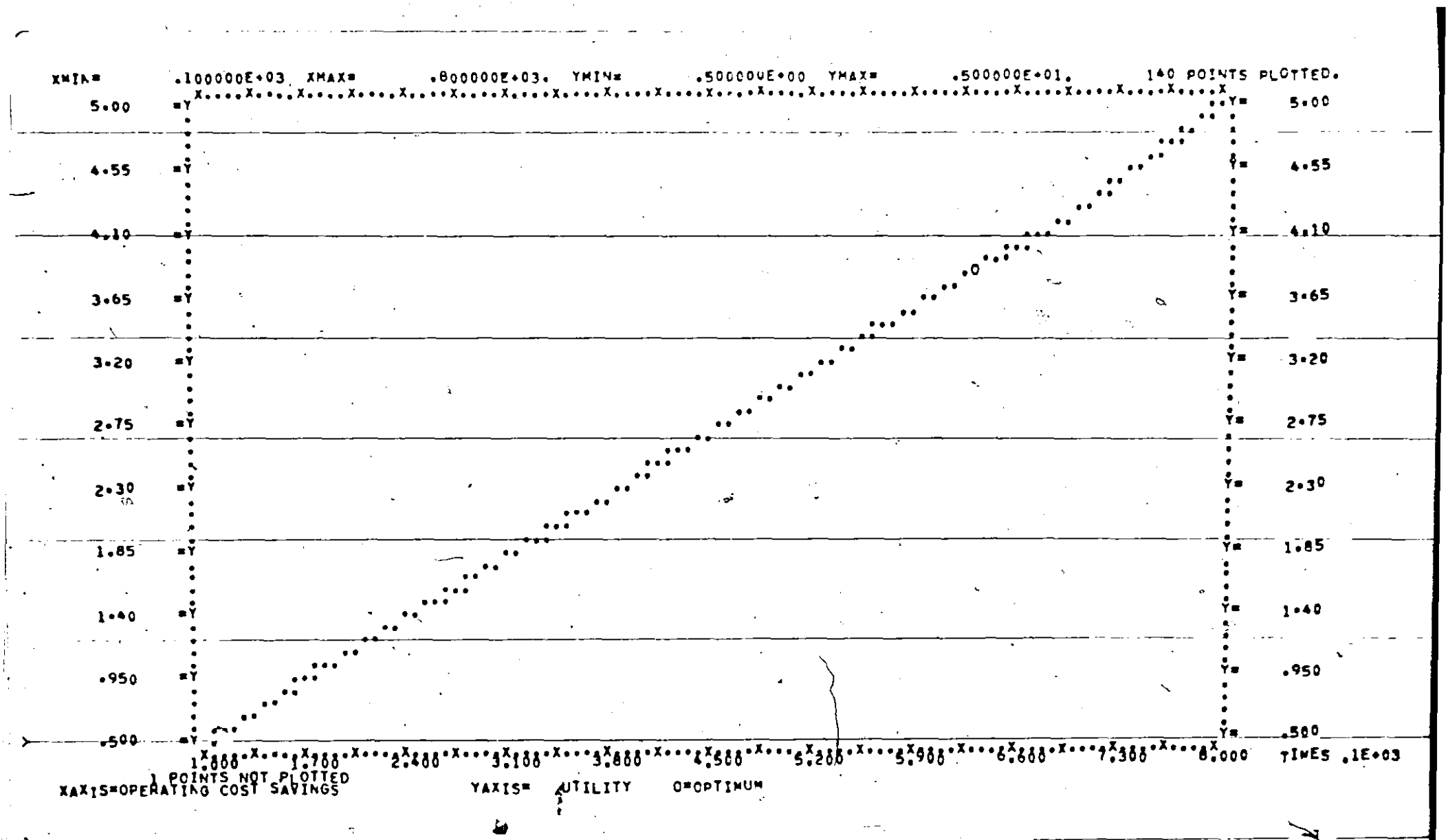


Figure 4 Variable X(2): Operating Cost Savings and Utility

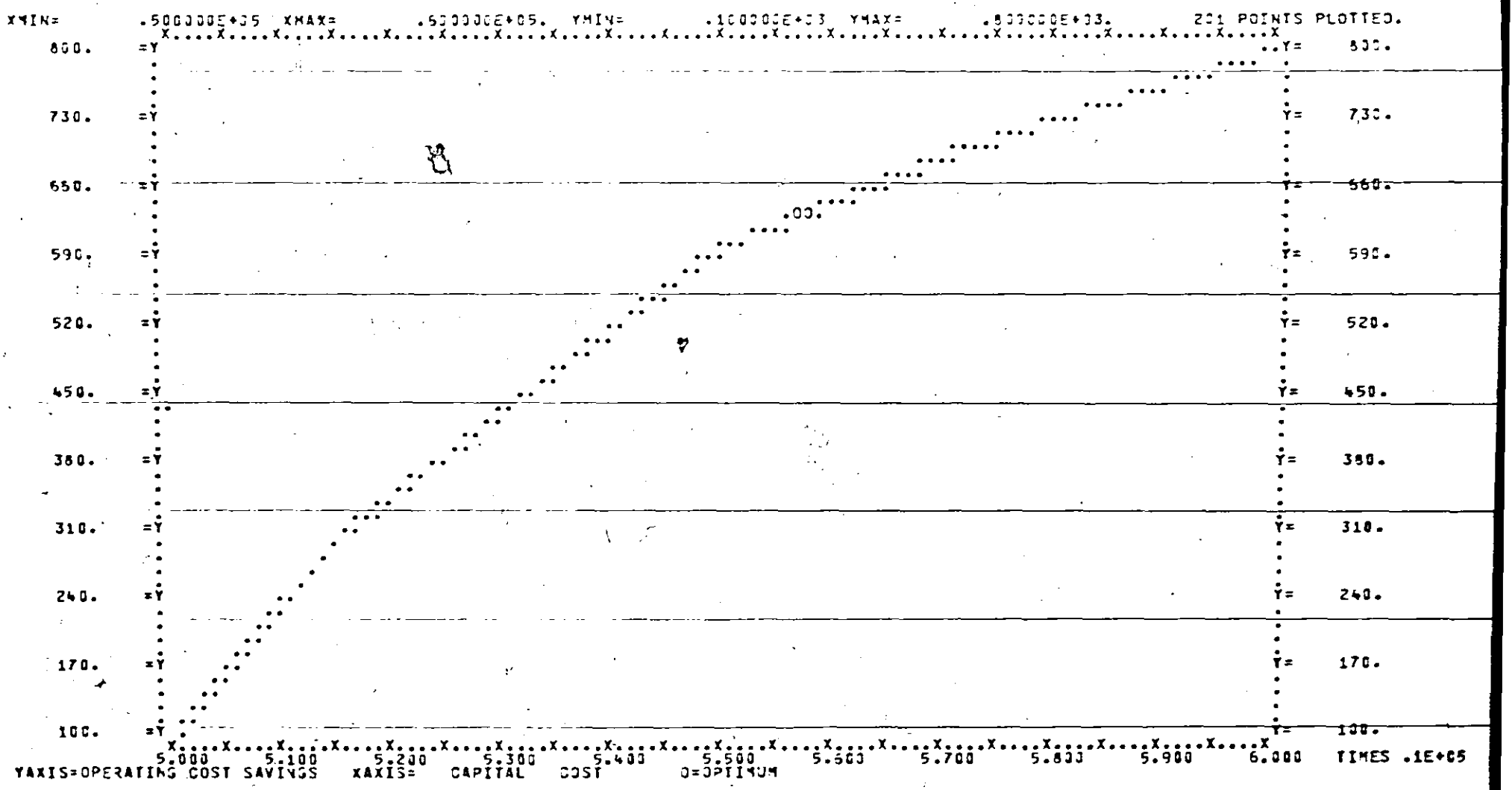


Figure 5 Variable X(2): Capital Cost and Operating Cost Savings

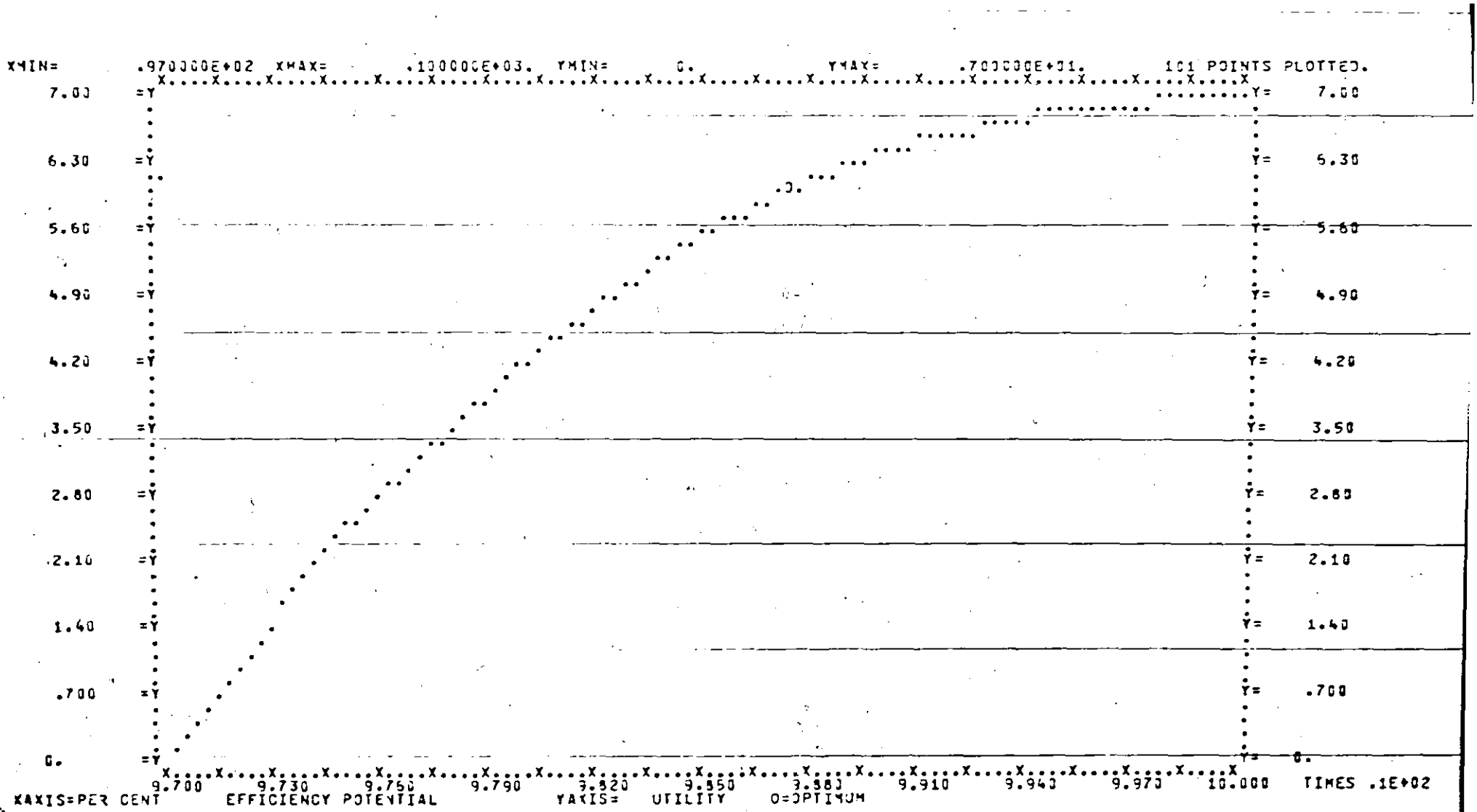


Figure 6 Variable X(3): Efficiency Potential in Per Cent and Utility

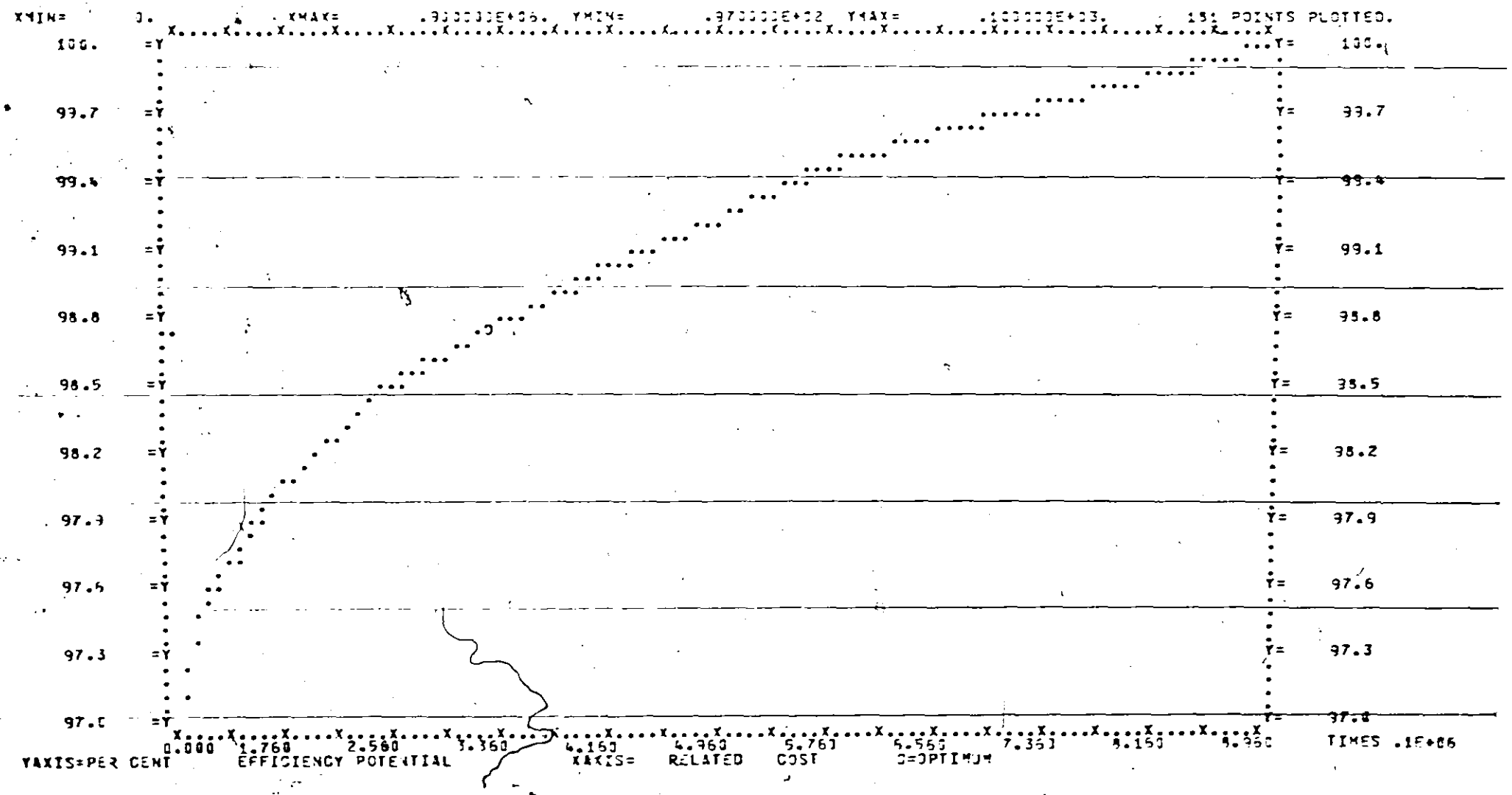


Figure 7 Variable X(3): Capital Cost and Efficiency Potential in Per Cent

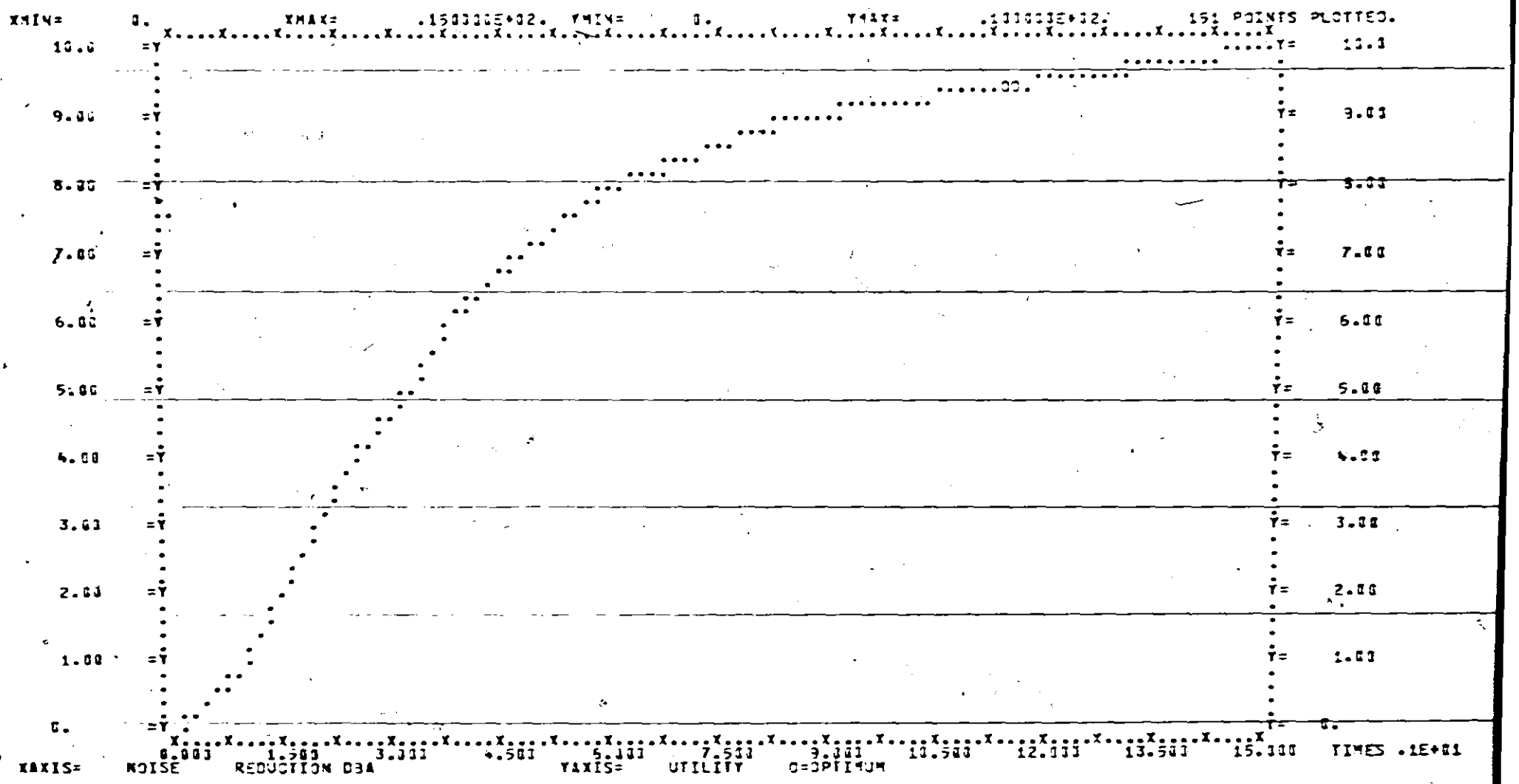


Figure 8 Variable X(4): Noise Reduction in dB(A) and Utility

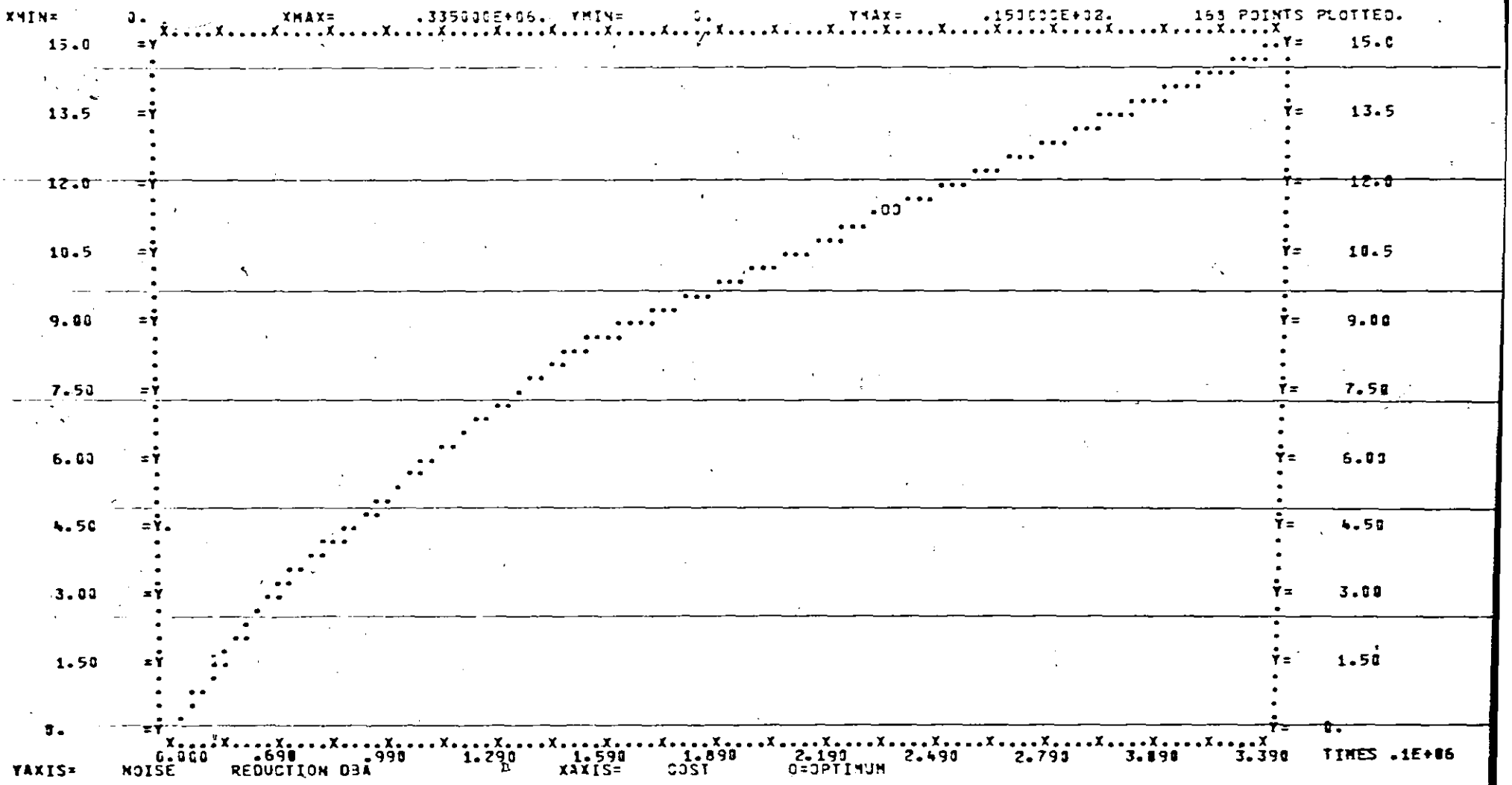


Figure 9 Variable X(4): Capital Cost and Noise Reduction in dB(A)

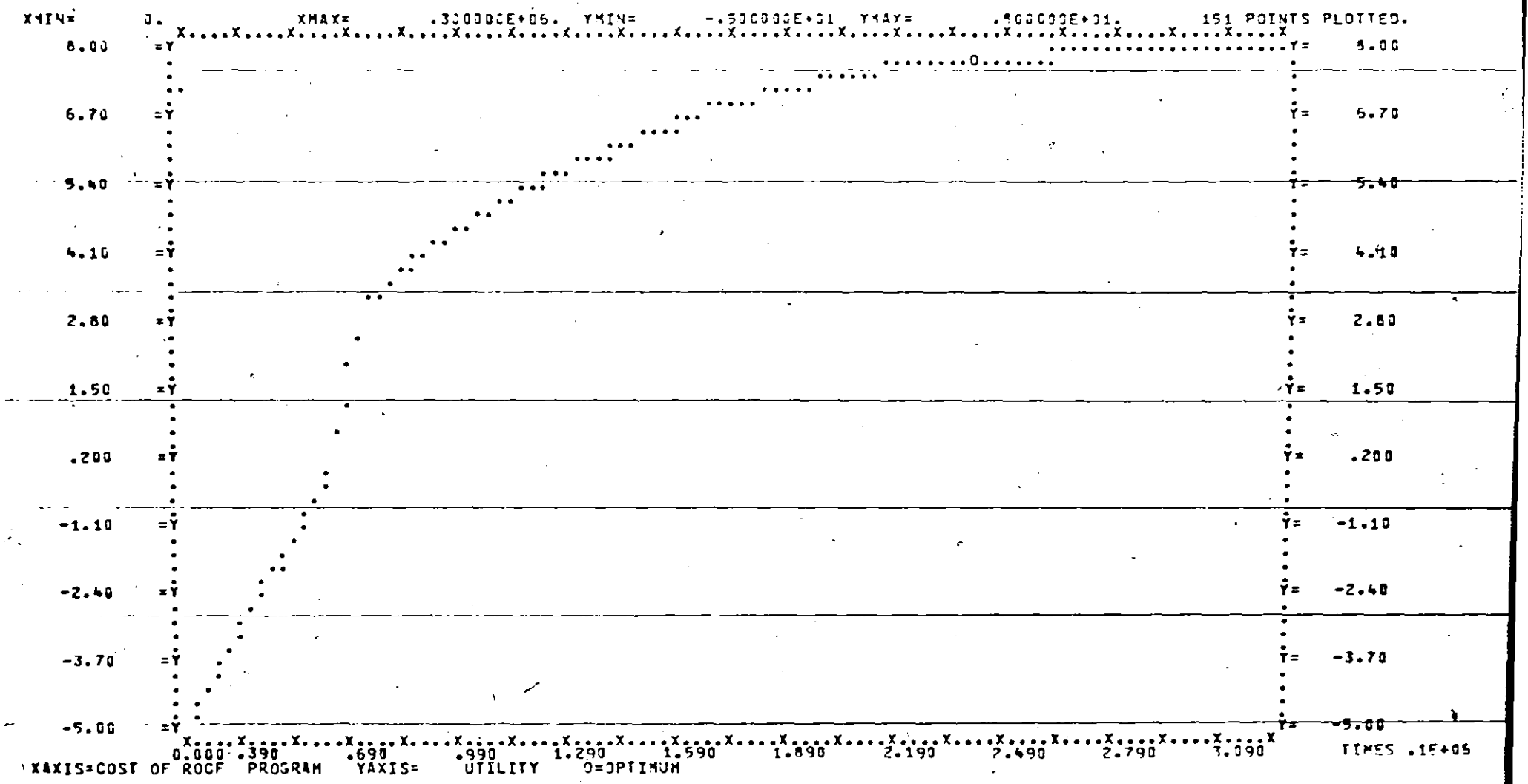


Figure 10 Variable X(5): Capital Cost of Roof Program and Utility

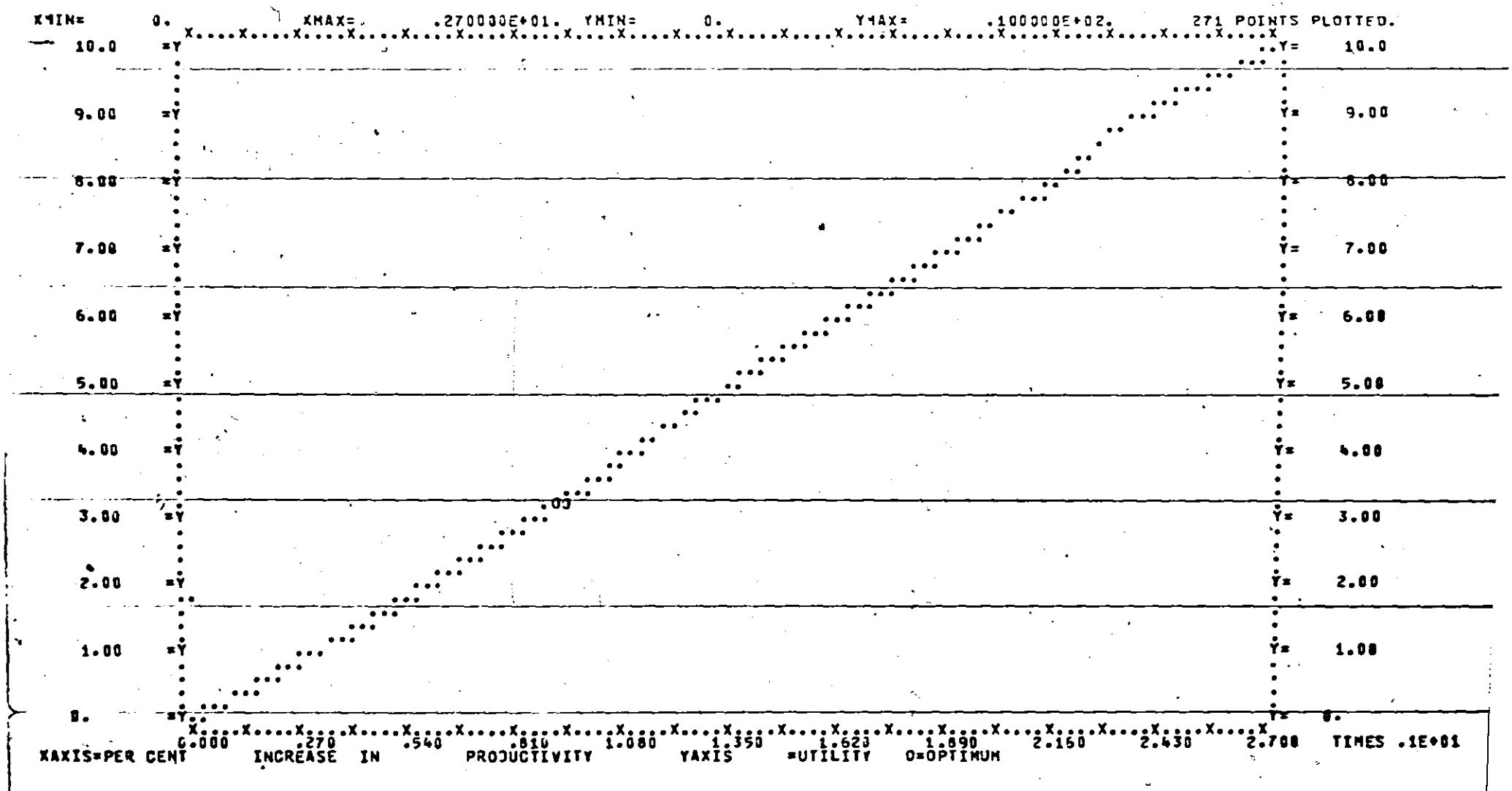


Figure 11 Variable X(6): Per Cent Increase in Productivity and Utility

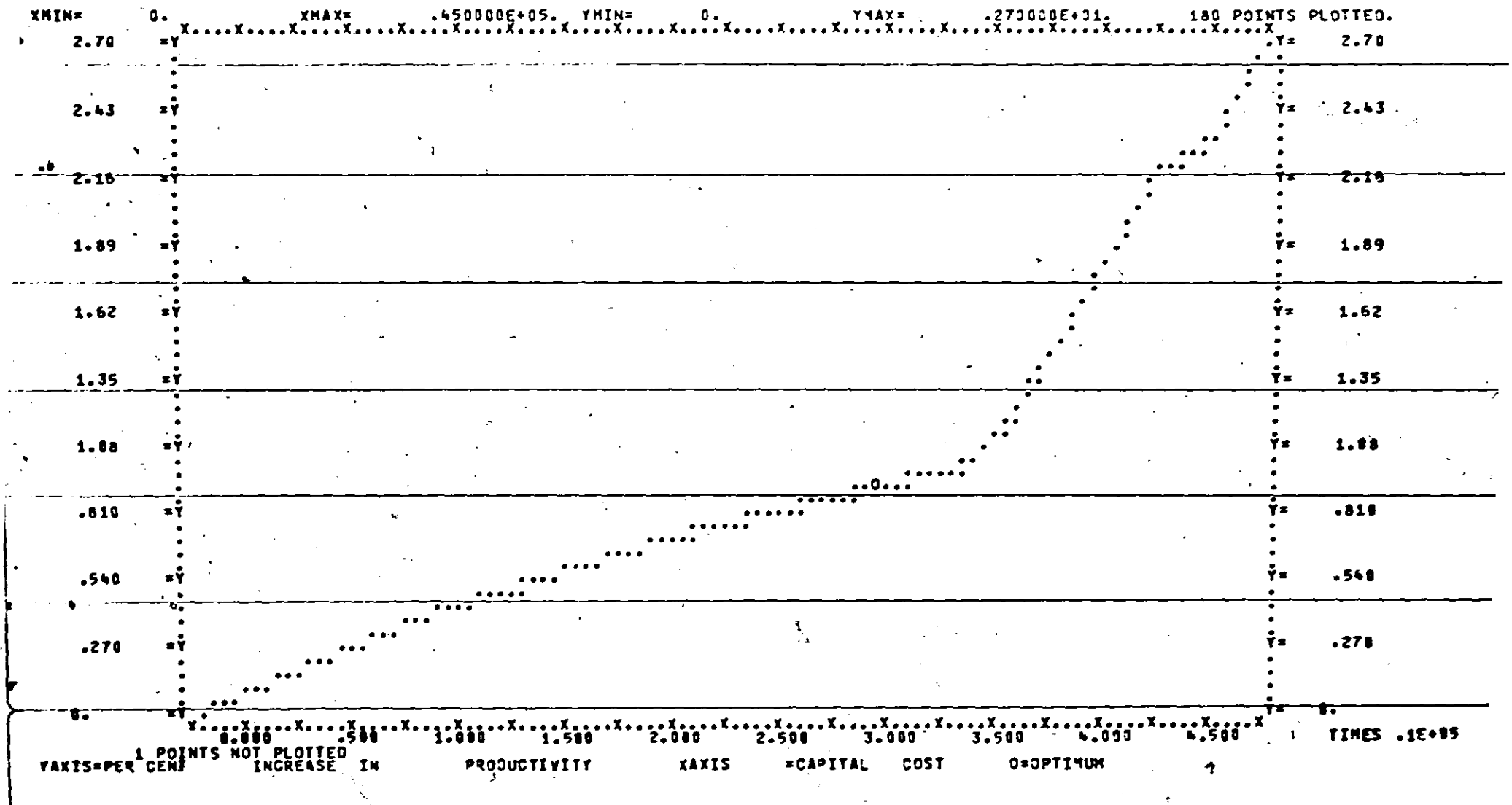


Figure 12 Variable X(6): Capital Cost and Per Cent Increase in Productivity

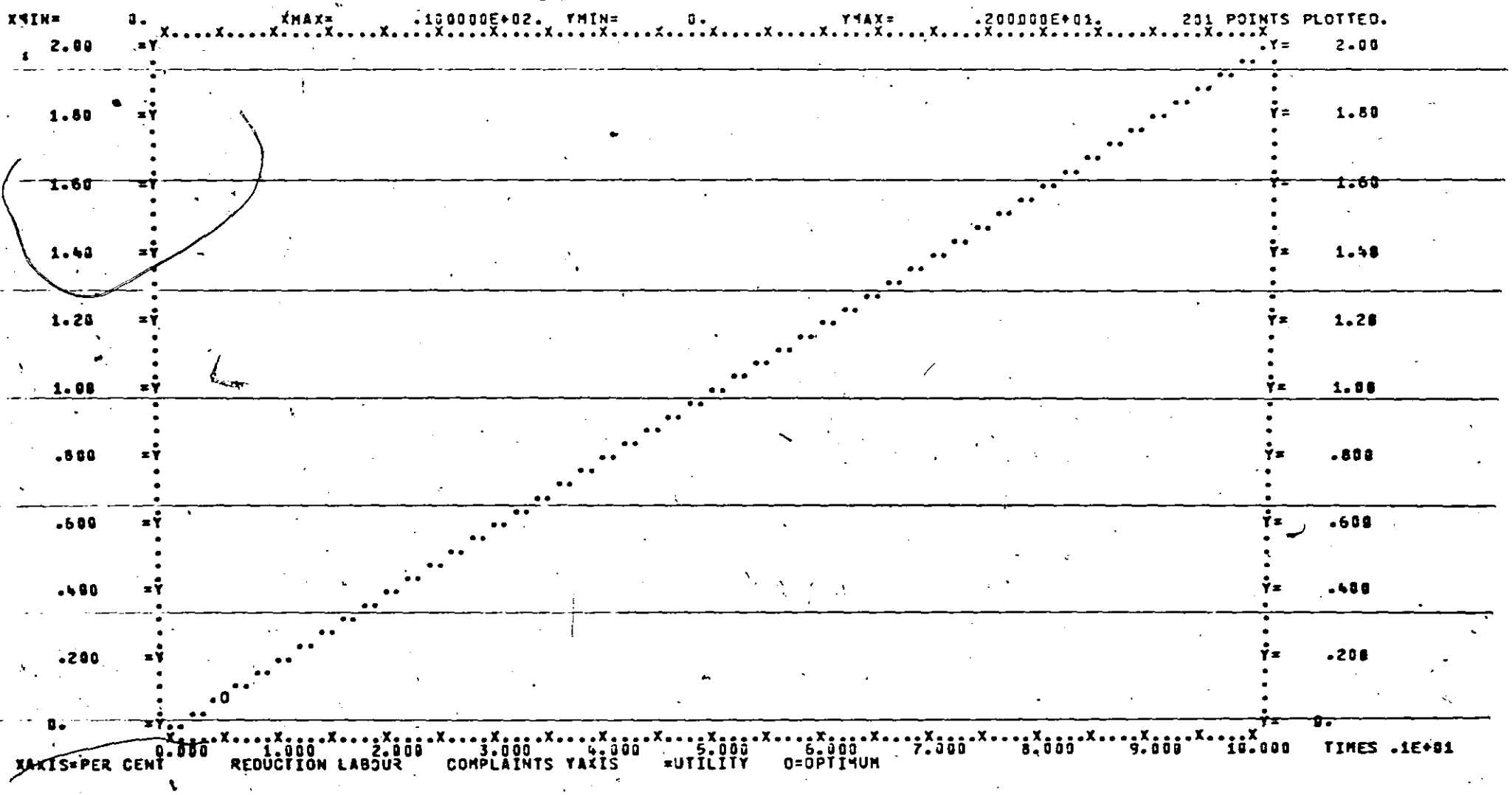


Figure 13 **Variable X(6): Per Cent Reduction of Labour Complaints and Utility**

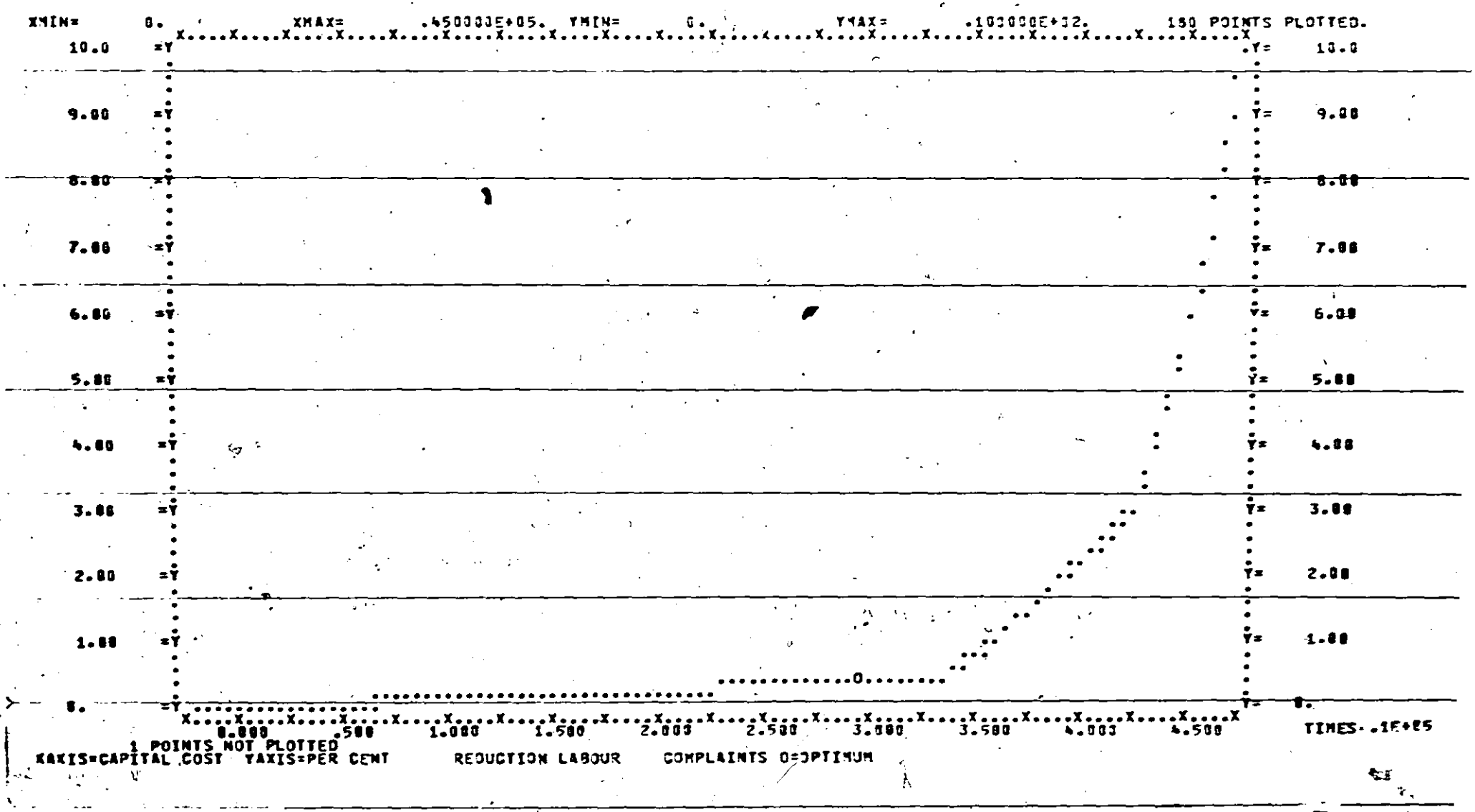


Figure 14 Variable X(6): Capital Cost and Per Cent Reduction in Labour Complaints

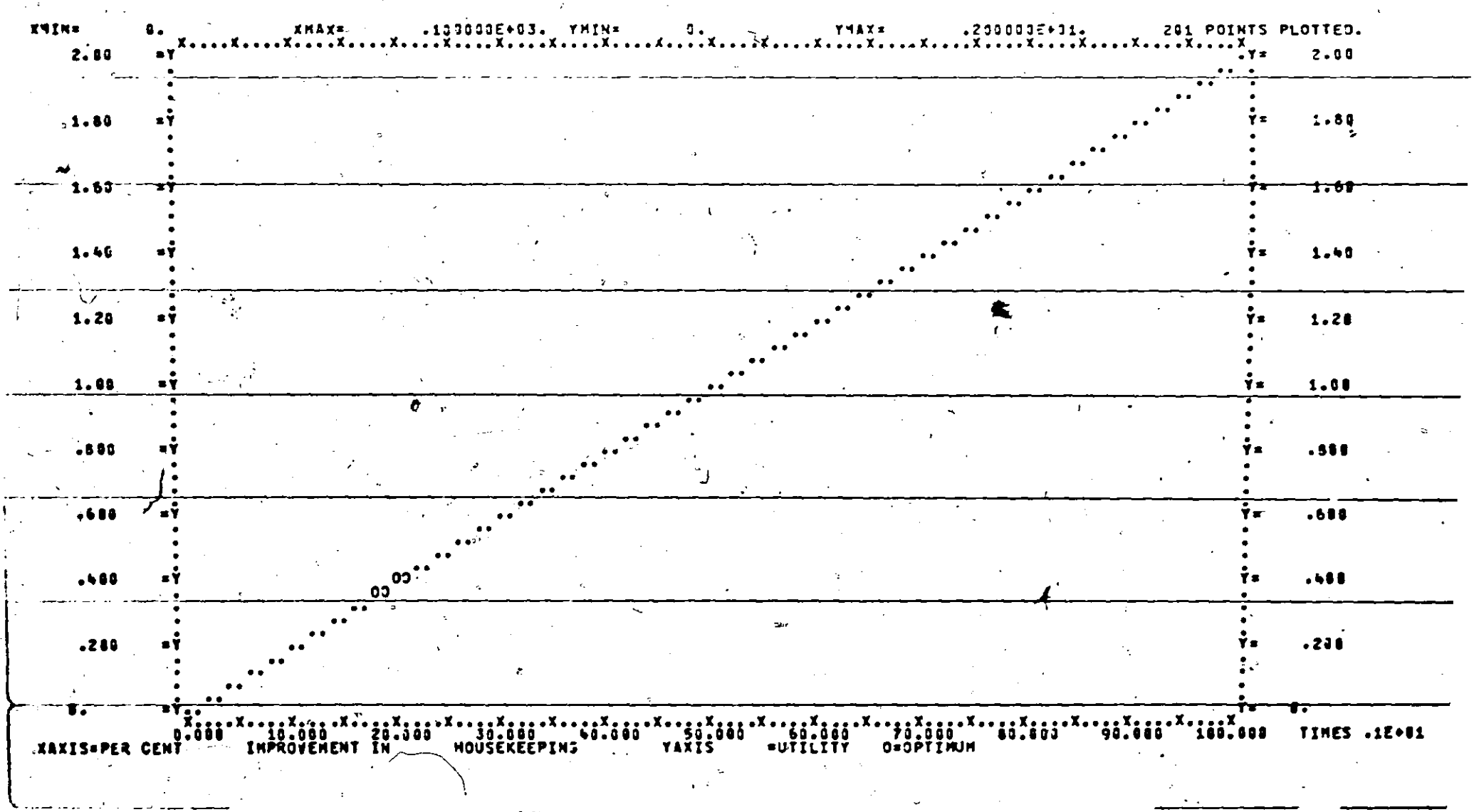


Figure 15 Variable X(6): Per Cent Improvement in Housekeeping and Utility

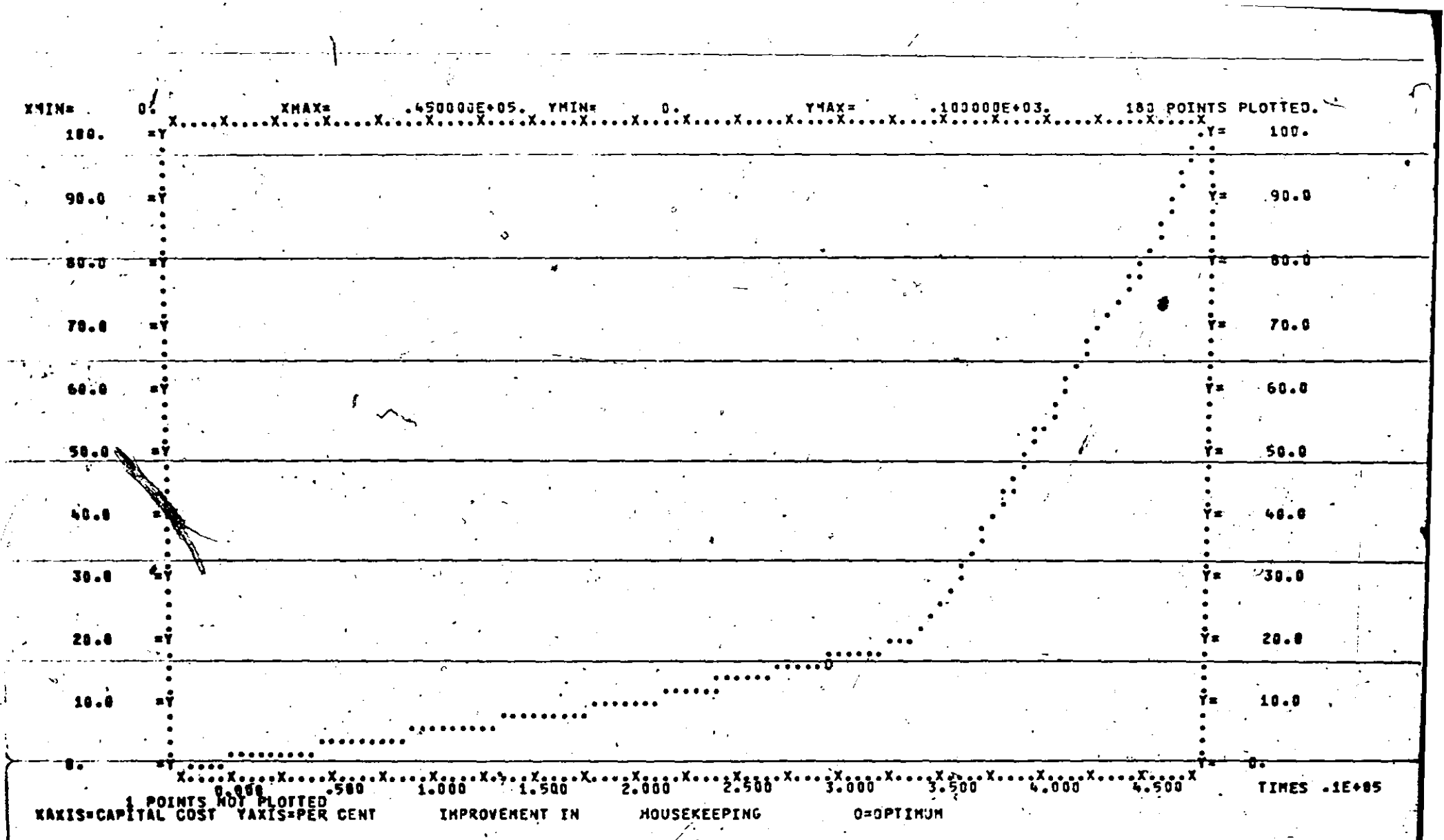


Figure 16 Varisble X(6): Capital Cost and Per Cent Improvement in Housekeeping

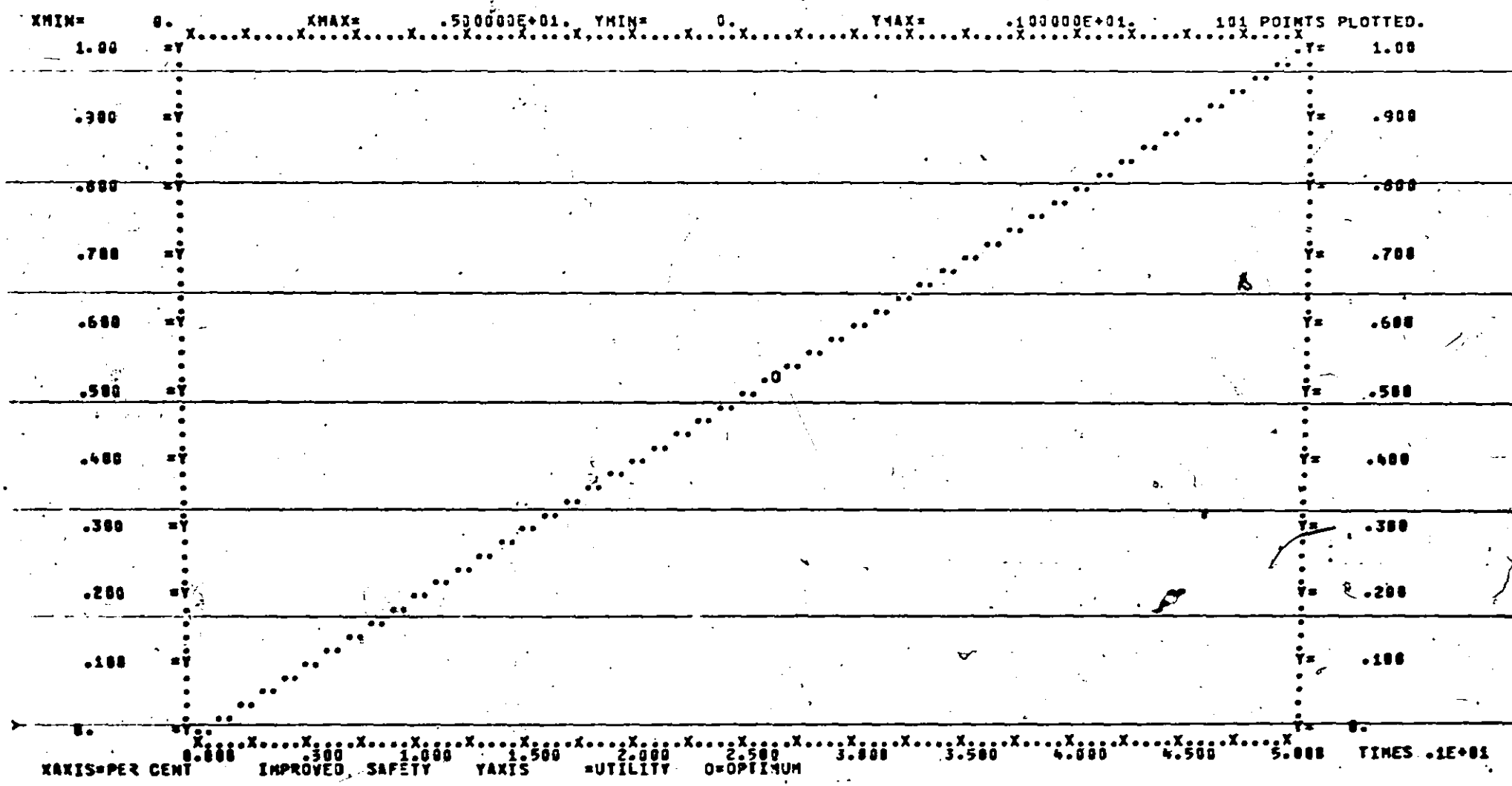


Figure 17 Variable X(6): Per Cent Improved Safety and Utility

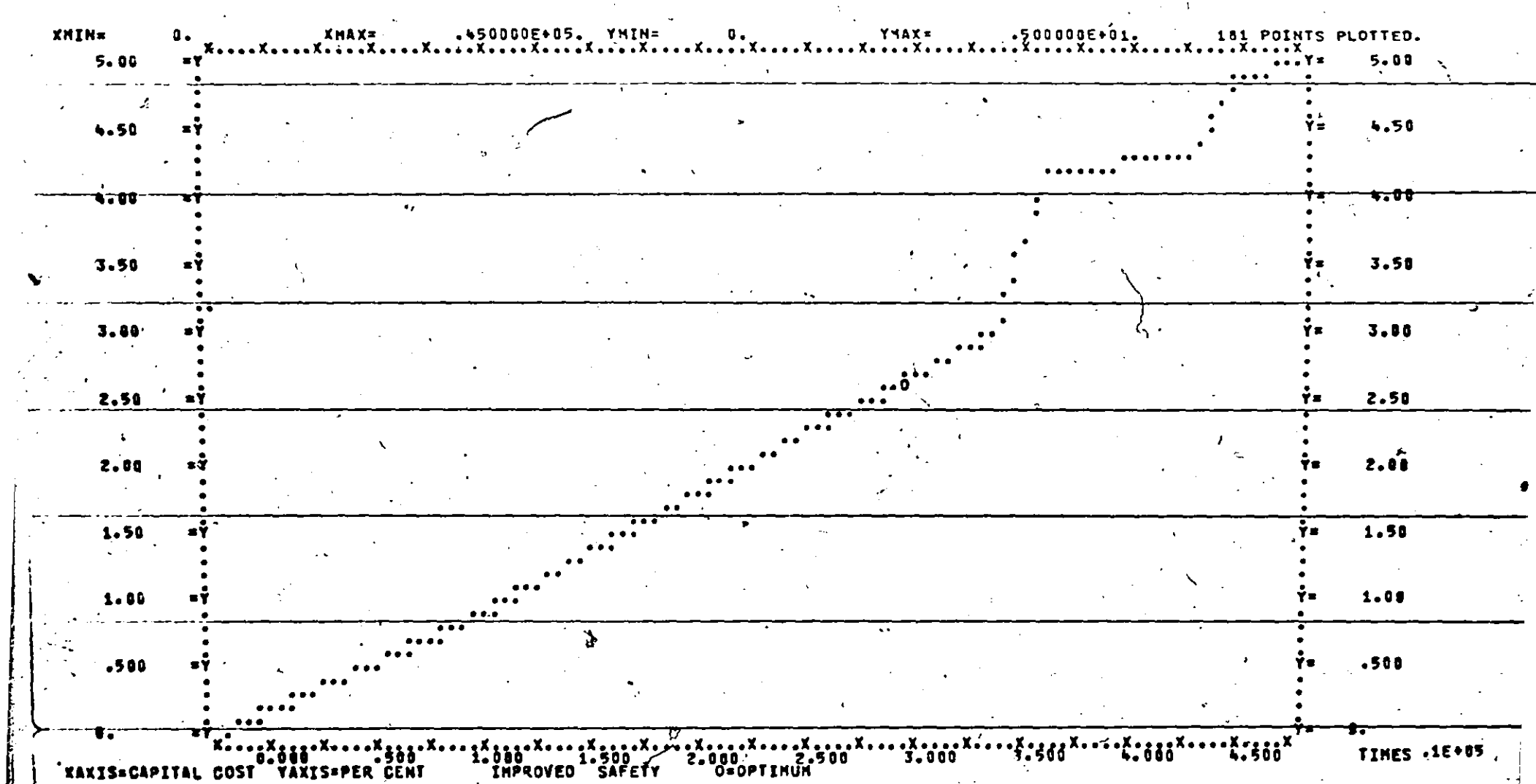


Figure 18 Variable X(6): Capital Cost and Per Cent Improved Safety

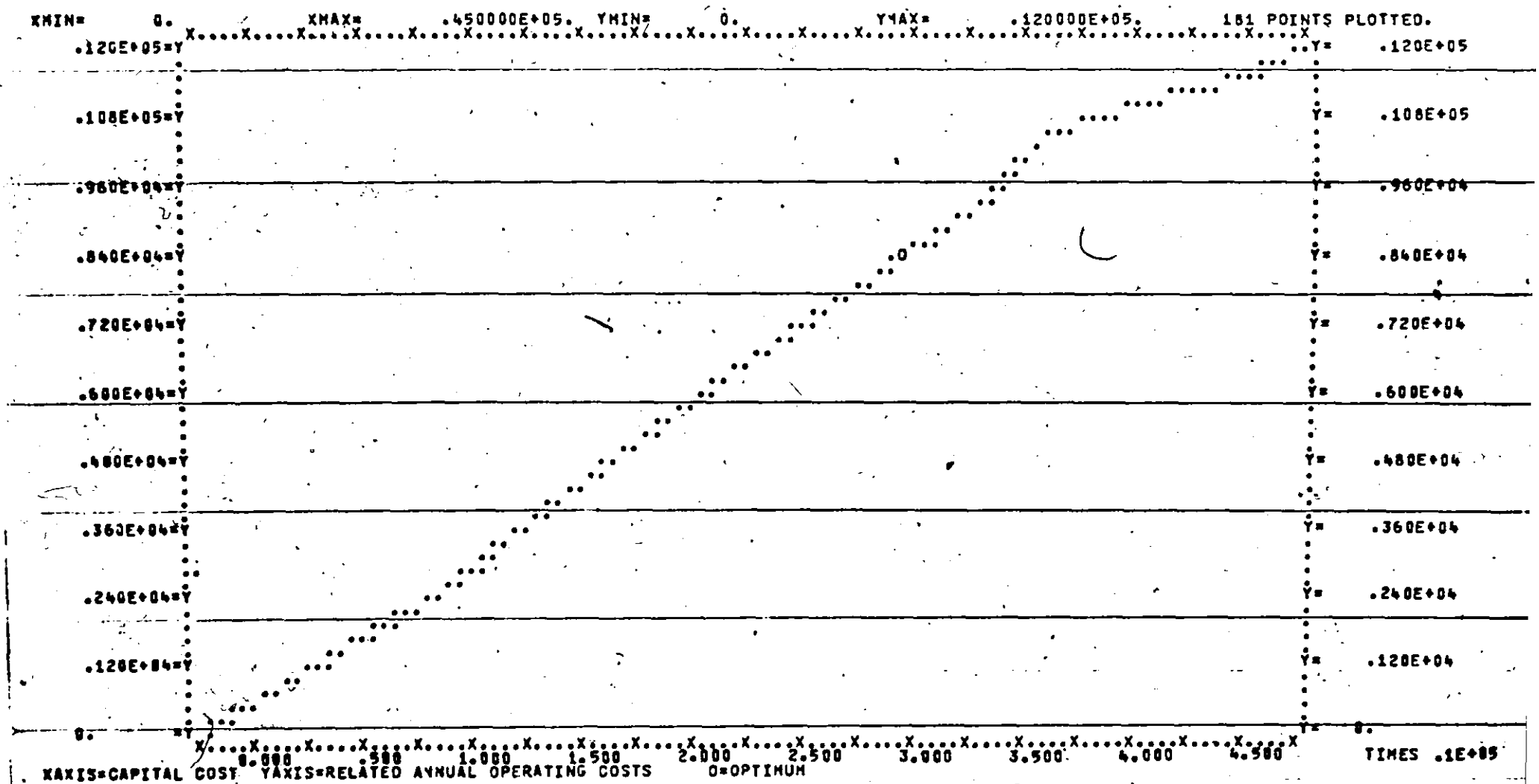


Figure 19 Variable X(6): Capital Costs and Related Annual Operating Costs

The computer program has two additional features. Should it be used at a later date when the probability of more stringent smoke emission limits is remote, variable X (3) would be a useless budget expenditure. The following output statements would occur:

VARIABLE X(3) IS NOT VALID
PROBABILITY OF FUTURE LEGISLATION
DOES NOT WARRANT A CAPITAL EXPENDITURE
RERUN PROGRAM WITHOUT X(3)

If the program does result in an optimum solution, but the return on investment for variable X (6) is economically unattractive due perhaps to rise in energy cost, the following output message would appear.

RETURN ON INVESTMENT FOR VARIABLE X(6) IS .GT. 5.0 YEARS
RERUN PROGRAM WITHOUT X(6)

The other variables are not subject to restrictive criteria, and do not require similar output messages.

The program developed for the thesis was run with several optimization subroutines in the OPTISEP package, SEEK 1, SEEK 3 DAVID, SIMPLX, and ADRANS, using a 40 octal second time limit, reasonable for this problem. Subroutine ADRANS was too slow for practical use; SIMPLX tended to hang up on the budget limit constraints; SEEK 1, SEEK 3, and DAVID found optimum solutions. DAVID is recommended for use with the type of problem developed in the thesis.

A summary of results is useful at this point:

TABLE 7

Optimization Subroutine	Computer Central Processor time (decimal seconds)	Value of optimization expression U = -(utility) Min.
SEEK 1	24.706	-31.755343
SEEK 3	24.848	-31.755343
DAVID	24.664	-41.339624
SIMPLX	27.488	-30.862295
ADRANS	Time limit	-37.56192 (at time limit)

Subroutines SEEK 1 allocated expenditures among the variables more evenly than subroutine DAVID, but subroutine DAVID found a better optimum point, therefore, DAVID can be considered the proper solution to the budget problem.

The optimization expression: $N = \sum \frac{1}{(\text{utility})}$ = minimum was used, along with $U = \sum(\text{utility})$ = maximum, without any appreciable change in results; that is, the values of the variables did not change appreciably. Varied starting values for the independent variable also had little effect on the results.

B. Analysis of Results

The output data is shown in numerical, descriptive and graphical form. After studying the results, management personnel can see the effects of sketching subjective utility values, and can see the effects of subjective weights. The graphical output duplicates the input data and pinpoints the optimum value of the variables. The author feels that such a visual presentation is valuable when assessing budget allocations.

If, say, variable X(4) appears slightly overemphasized, its weighting can be dropped on a scale of 10, from 10 to perhaps 8; the computer program can be modified and re-run within thirty minutes. The new output would automatically reshuffle all budget allocations to a new optimum. Of value, when working with a real budget at this point, would be a sensitivity analysis to determine exactly the effects of minor curve changes.

If the optimum points on the utility curves are not high enough to satisfy the plant engineering department, the proposed budget limitation can be increased from $ 1,000,000.00 to possible $ 1,200,000.00. Again only thirty minutes would be required to modify the program, re-run it and end up with a new set of budget allocations and curves. A sensitivity analysis would also be of value when using real data, to assess effects due to budget changes.

If one variable must be added to or deleted from the budget at a later date, a new budget allocation could be produced within an hour, to reflect the results of the changes.

The flexibility of this approach to budget development could save many hours of calculations, and ensure that a consistent form of logic is used at all times. The program was run as a batch input. Note, that an interactive time-sharing version of the program would reduce modification time considerably, especially with an office terminal.

This analytical approach does not replace any decision-making duties of management, but it does clearly display management thinking; it does help management to make value-judgments about social and environmental problems; it codifies their subjective values, and it does show management the real cost of solutions and the effect of limiting environmental budgets.

The computer program was shown to be sensitive to energy operating costs particularly for variable X(6), a valuable feature in view of General Motors goal of 15 percent energy usage reduction, beginning in 1973. (19)

The experimental program involving light and colour, variable X(6), has some interesting applications. A housekeeping expenditure could be justified on the basis of the return on investment due to its effect on productivity. Similarly a safety program, involving lighting and painting, could be justified by the resultant productivity gains.

Little more than a course in optimization, and a basic knowledge of programming are required to use optimization effectively. The budget developed in this thesis does contain realistic variables, but it is not, as previously mentioned, representative of a complete

plant engineering budget. If this approach is used on such a large budget, with many variables, the usefulness of optimization to logically and quickly assimilate data and produce results would be magnified.

X. CONCLUSIONS

Optimization coupled with utility theory has been demonstrated as a useful tool when assessing budget allocations. The advantage of using this tool is better decisions. The technique requires that management make value-judgments about social and environmental problems, with the end result being a logical assessment of the dollar value of subjective aspects of environmental problems.

One must remember, however, that subjective values are difficult to measure. Further research is needed to determine the optimum method of assessing utility values in the particular industrial environment described in this thesis. The procedures described in this thesis can be time-consuming, and the relationship between time spent on sketching and scaling verses improved quality of budget allocations needs to be investigated further. In any case, the procedures as described can improve the quality of decisions concerned with subjective values.

The budget developed in this thesis required not only allocation of funds to subjective areas; but also considerations of return on investment, probability, the time value of money, inflation, and operating costs. All of these aspects of budget development were handled by one relatively simple, flexible, computer program; computer central processing time was consistently less than 30 seconds.

In this thesis the author has presented one example of the use of optimization and utility theory in the environmental control systems field, applicable to General Motors Corporation.

APPENDICES

APPENDIX A

Time Value of Money

Time Value of Money (3)

In order to combine different monetary values, which may occur at different times, it is necessary to have techniques which will establish monetary equivalents at different times, based on interest.

We must begin by defining the following quantities.

S_n = future payment

P = present worth or initial investment

R = periodic payment

i = interest rate per period, in dollars per dollar

n = number of periods

These quantities can be related by inductive arguments as shown in Table 1 below.

Table 1 Time Relationships Between Monetary Quantities

	Input	Multipy By	Output
1	P	$(1 + i)^n$	S_n
2	S_n	$(1 + i)^{-n}$	P
3	R	$\frac{(1 + i)^n - 1}{i}$	S_n
4	S_n	$\frac{i}{(1 + i)^n - 1}$	R
5	R	$\frac{(1 + i)^n - 1}{i\,(1 + i)^n}$	P
6	P	$\frac{i\,(1 + i)^n}{(1 + i)^n - 1}$	R

To illustrate the use of the table, we assume that we wish to find the initial investment equivalent to n periodic payments of amount R. We use relationship 5.

$$P' = \frac{(1 + i)^n - 1}{i\,(1 + i)^n} \cdot R$$

Combining Monetary Values

Using the relationships of the previous section, we may now combine different monetary values, by bringing them all to the same form.

APPENDIX B

Data for Table 5

Development of Costs for Step 1 in Table 5

Type of Luminaire Used:

Electrolier (semi-direct industrial type fixture), "50" series Pathfinder H - 50 - 296, for two 105 watt H.O. T - 12 96" fluorescent lights.

Typical Lamp:

Sylvania 800 ma, High Output Rapid Start Lifeline Lamp, 105 watt, 96" recessed double contact (F96 T - 12/CW/HO), cool white, with a 9000 hour life on a three hour cycle. Initial lumens 9500 (rating taken after 100 hours). Average sustained lumens, 8200, measured at 40% of rated life.

Cost of Luminaire and Lamp: $ 125.00

Cost of Installation above Rotor Machinery Area:

In this 22,800 square foot area there is room to mount a luminaire to existing supports located between existing luminaires. The existing transformers could handle a doubling of the current lighting load. Estimated installation cost is 4 hours labour x 6.00 per hour = $ 25.00 plus $ 125.00 material for a total cost of $ 150.00. Actual lighting level averages from 20 to 40 footcandles at working height, from 216 existing luminaires.

Maintenance Factor: Fair or 0.60*

Coefficient of utilization based on 10 per cent floor reflectance, 50 per cent ceiling reflectance and 50 per cent wall reflectance the coefficient of utilization is C.U. = 0.75*

* Sylvania brochure

Room Ratio:

Dimensions of rotor area 190 feet by 120 feet with lights 14 feet above floor.

Room ratio is:

$$\frac{190 \times 120}{14\ (190 + 120)} = 5.25 \text{ or } 4^*$$

Calculated current lighting level in footcandles:

$$\text{footcandle} = \frac{8200 \text{ lumens} \times 216 \text{ luminaires} \times 0.75 \times 0.60^*}{22{,}800 \text{ sq. ft.}}$$

$$= 35, \text{ favorably comparing with actual levels.}$$

Number of additional luminaires that could be added with a minimum of expense: 210 additional luminaires can be supported and powered by existing supports and transformers.

Light level expected with additional of 210 luminaires:

$$\text{footcandles} = \frac{8200 \text{ lumens} \times 210 \text{ luminaires} \times 0.75 \times 0.60^*}{22{,}800 \text{ sq. ft.}}$$

$$= 70$$

Capital Cost: 210 luminaires x $ 150.00 = $ 31,500.00

Note that a lighting level of 70 footcandles was reasonable as determined by the Illuminating Engineering Society recommendations. The addition of the 210 luminaires was the most economical step to increase lighting, and uses current stock items. Expected productivity gains were based on a lighting level of 70 footcandles for step 1, and a slightly increased level due to step 2 (C.U. = 0.84, level 78 footcandles).

* Slyvania brochure

Annual Operating Cost of Additional Luminaires:

1. Power costs are: 250 watts per fixture or 250 x 210 = 54 kilo watts for 210 fixtures. Power costs based on 24 hour operation is 54KW. x 24 hr. x 365 days x 1½¢ per KW = $ 7,000.00 per year.
2. Annual cost of cleaning lights and luminaire: $ 7 x 210 = $ 1,500.
3. Cost of replacing lamps annually if done when luminaires are being cleaned = $ 3 x 210 = $ 650.00. Note that one year or 8750 hours of operation approaches 80% of expected life of the lamps (9600 hours)
4. Spot replacement, annual cost: $ 350.00

Total annual operating costs are 1. + 2. + 3. + 4. or $ 9,500.00

The current lighting level was calculated using the more detailed procedure outlined in the Illuminating Engineering Society Lighting Handbook, Fifth Edition, Chapter 9 . The purpose was to check the accuracy of the short method available in the Sylvania brochure. Pages referred to are in the I.E.S. Handbook. (17)

Cavity Ratios :

$$= \frac{5h\ (\text{Room length and room width})}{(\text{Room Length}) \times (\text{Room Width})}$$

hrc = average of 6 feet.

$$\text{Ceiling Cavity Ratio, CCR} = \frac{5 \times 6\ (190 + 120)}{190 \times 120} = .4$$

hrc = 11 feet

$$\text{Room Cavity Ratio, RCR} = \frac{5 \times 11(190 + 120)}{190 \times 120} = .75$$

hfc = 3 feet .

Floor Cavity Ratio = $\frac{5 \times 3 (190 + 120)}{190 \times 120}$ = .2

Per cent Effective Ceiling Cavity Reflectence, ρ_{fc} , is based on Ceiling reflectence of 50 per cent, wall reflections of 50 per cent, and CCR = .4

ρ_{cc} = .47

Per cent Effective Floor Cavity Reflectance, ρ_{fc} , is based on floor reflectance of 10 per cent, wall reflectance of 50 per cent, and CCF = .4

ρ_{fc} = .10

Coefficient of Utilization, based on ρ_{cc} = .47, ρ_{fc} = .10 and luminaire 30, yield from Fig 9-12, C.U.=.75. The C.U. is adjusted by Fig 9-13 to C.U.' = .75 x .956 = .73. The result is close to the .75 estimated from data in the Sylvania catalogue.

Light loss factors, see pages 9-1 to 9-8 in the I.E.S. Lighting Handbook and Fig. 10, Chapter 1, A.F.S. Environmental Manual. (2)

Light Loss Factor	Value
1. Luminaire abcent temperature	.95
2. Voltage to Luminaire	.98
3. Ballast factor	1.00
4. Luminaire Surface Depreciation	.98
5. Room Surface Depreciation	.92
6. Lamp Lumen Depreciation	.80
7. Lamp burnout factor	1.00
8. Lumen Depreciation	.90

Data Source for Factors

1. AFS Manual
2. pg. 9-3
3. pg. 9-4
4. estimate
5. pg. 9-4, 12 month, medium
6. Sylvania catalogue
7. Spot replacement to be carried out between annual re-lamp progress
8. Class 11, Medium, pg. 9-5, 9-6

Light Loss Factor LLF = .95 x .98 x .00 x .98 x .92 x .80 x 1.00 x .90

= .605 ≅ .6

Expected current lighting level of 216 existing luminairies

$$\text{footcandles} = \frac{216 \times 9500 \times .75 \times .60}{22{,}800} \quad \text{(pg. 9-7)}$$

= 39

This level compares favorably with the calculation based on the Sylvania catalogue, of 35 footcandles. The simpler Sylvania method will be used in further calculations.

Development of Costs for Step 2, Table 5

Paint cost: $ 10.00 per gallon

Coverage: 500 sq. ft. per gallon

Labour: 500 sq. ft. of ceiling area above floor space per day

Area: 22,800 sq. ft. of floor area

Labour: 22,800 ÷ 500 = 46 man days at $ 6.00 per hour, based on an 8 hour shift 46 x 8 x 6 = $ 2210.00. Additional allowance of $ 190.00 for difficult to paint areas

Material: 60 gallons x $ 10.00 = $ 600.00

Total Capital Cost: $ 3,000.00

Resultant effect on lighting level:

White reflectance is greater than 80%, C.U. becomes .84 and level in footcandle increases from 35 to 39, or 70 to 78. Annual maintenance cost, $ 1,000.00.

Development of Costs for Step 3, Table 5

Paint cost and coverage as in Step 2.

Labour: clean and paint machinery over a 200 sq.ft. floor area per 8 hour shift.

Paint Required: 55 gallons

Cost of Labour: 22,800 ÷ 200 = 114 man days

114 x 8 hr. x $6.00 = $ 5,472.00

Cost of Paint: 55 x 10. = $ 550.00

Total Cost: $ 6022 ≐ $ 6,000.

Estimated maintenance cost based on 10 year life of paint is $ 600.00 per year.

Development of Costs for Step 4, Table 5

A.N.S.I. Pipe Code and Safety Code are slightly different that General Motors standards.

Labour Costs: Estimated time is based on repainting re-identifying pipe and safety markings at the rate of 600 sq.ft. of floor area per 8 hour shift

Area: 22,800 sq.ft.

Cost of Labour: (22,800 sq.ft. ÷ 600 sq.ft.) x 8 hr. x $6. per hour
= $ 1,800.00

Cost of Material: $ 200.00

Total Capital Cost: $ 2,000.00

Operating costs to handle piping and safety equipment relocations are estimated at $ 200.00 per year.

Development of Costs for Step 5, Table 5

Cost of Labour:

Painting 240 hr. x 6 = $ 1,440.00

Electrical work (lighting) 80 hr. x 6 = $ 480.00

Material $ 500.00

Total Cost: $ 2,420.00 - $ 2,500.00

Estimated annual operating costs: $ 250.00 is required to handle modifications due to machinery additions and relocations affecting employee eating and working areas.

A P P E N D I X C

Program Listing

and User's Manual

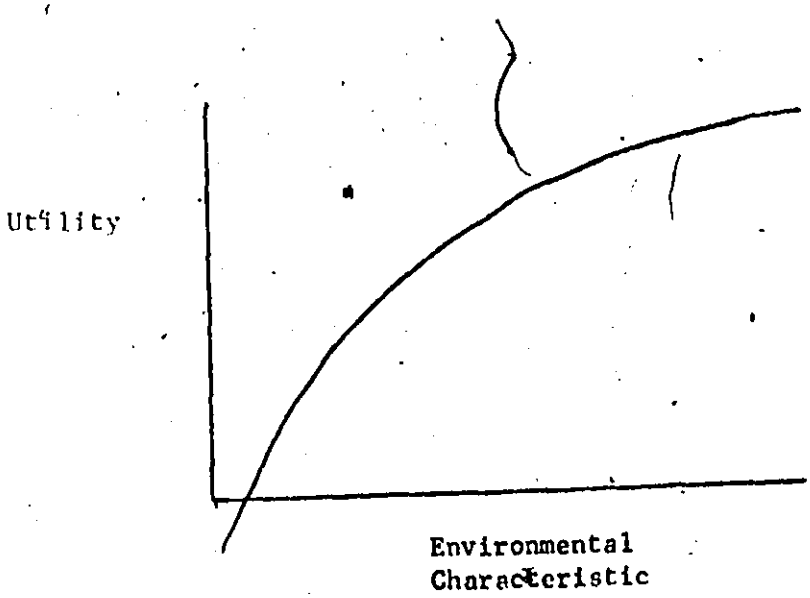
USER'S MANUAL FOR CAPITAL BUDGET ALLOCATION OPTIMIZATION PROGRAM

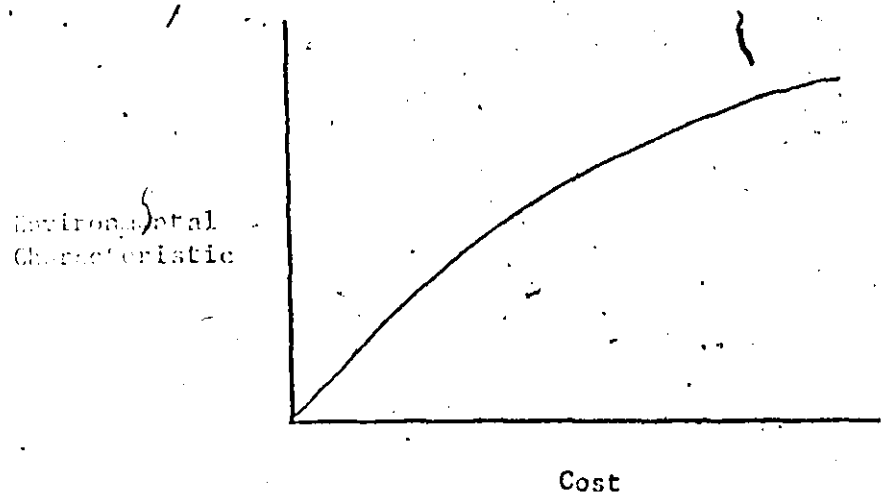
I. Introduction

The program uses utility functions to evaluate budget expenditures on environmental characteristics that enhance a company's position or future in some non-monetary way. The program allows a logical comparison of social, political, and other non-technical items, while forcing management to make consistent values judgements in these subjective areas. The value of each variable is expressed in terms of unitless utility.

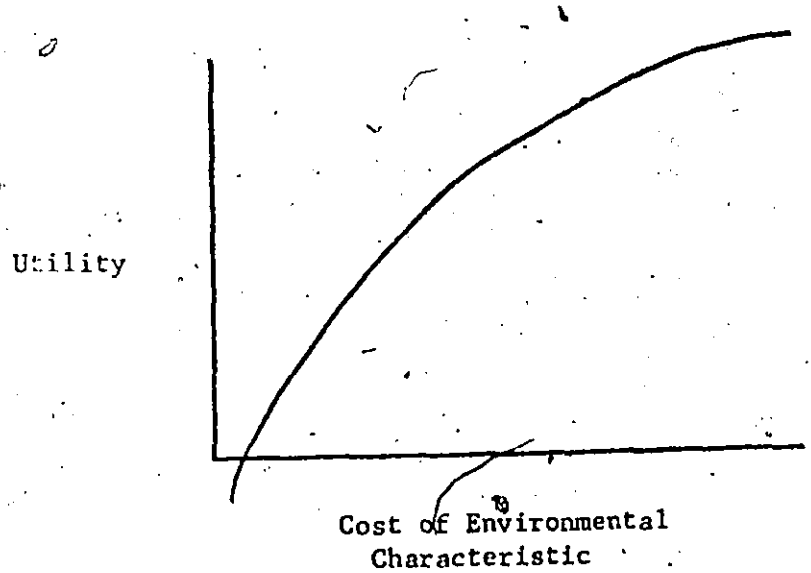
II. Application of Utility Functions

The relationship between the independent variable (cost); the dependent variable, or environmental characteristic (such noise reduction, adaptability, housekeeping, or good will); and its utility is expressed with utility and cost curves. Generally the relationship takes the following form:





The utility curve is subjectively developed; the cost curve is based on engineering data. Occasionally the environmental characteristic can not be measured directly and the relationship between utility and cost is expressed directly:



Utility and cost curves must be developed for each independent variable and related dependent variable. Note that several dependent variables may be associated with one independent variable.

Next, the utility curves must be weighted, in order to express the relative importance of the dependent variables (environmental characteristics).

III. Optimization Expression

As discussed in Prof. J.N. Siddall's text (3) concerning multi-factor optimization, two approaches can be used:

U = (utility value of each dependent variable)

= maximum

or $U = \frac{1}{\text{(utility value)}}$ = minimum

Both expressions work equally well.

IV. Input Data and Program Format

For each variable the following input must be entered in the main program, with all data coming from the utility and cost curves.

DATA COST/ M points on cost curve/ (5 or more)

DATA VARIABLE/ corresponding values of the dependent variable/

DATA UTILITY/ corresponding units of utility/

Function FTABLE will interpolate between these points to form a continuous curve, approximating the original utility or cost curve. For any given point XX, on a cost curve

Z = VALUE OF DEPENDENT VARIABLE = FTABLE (COST, VARIABLE, XX, M) and

ZZ = CORRESPONDING UTILITY = FTABLE (VARIABLE UTILITY, Z, M)

The remainder of the main program follows the outline provided in Reference (4)

Utility and cost curves must be developed for each independent variable and related dependent variable. Note that several dependent variables may be associated with one independent variable.

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ZZ = CORRESPONDING UTILITY = FTABLE (VARIABLE UTILITY, Z, M)

The remainder of the main program follows the outline provided in Reference (4)

Data can be transferred to subroutines UREAL and CONST by the use of COMMON cards. Subroutines UREAL and CONST must also be user written as shown in the OPTISEP manual, Reference (4) Note that the optimization expression will contain the sum of the utility values for the variables.

Function FTABLE must also be included in the program as shown in the program listing.

V. Output Information

By following these input requirements, output showing the optimum budget expenditures will results as shown on Page 73 on the thesis.

If desired, simple format statements can be written into the main program for an output similar to Page 74 of the thesis.

In addition, output curves can be developed, by utilizing subroutine PLOTPT in the main or calling program. Refer to Reference (11) for details.

The optimum points on each curve can be singularly identified in the output graphs by adding a simple DO loop, when writing subroutine PLOTPT into the calling program. This feature is not a part of subroutine PLOTPT; therefore an example is included:

The following statements were used to plot per cent increase in productivity (range 0 to 2.7) on the X axis, and utility (range 0 to 10) on the Y axis.

```
AX = 0.0 (starting value of per cent increase productivity on X axis)
A6 = CPROD + 0.4 (optimum utility value plus a small increment)
501 ZPROD = FTABLE ( YPROD, UPROD, AX, 8), where ZPROD is the utility
value, using function FTABLE.
IF (AX. GE. CPROD AND AX. LE. A6) GO to 507
CALL PLOTPT (AX,ZPROD,9)  (ie, print a dot for this point)
508 AX=AX+0.01  (ie, increment the value of AX)
```

IF(AX.GT.2.7)GO TO 511

(ie, if the value of per cent productivity has exceeded maximum range,

go to 511 and stop the iteration)

GO to 501 (and calculate the appropriate utility value for the incremental value of AX)

507 CALL PLOTPT (AX, ZPROD, 35)

(ie, print an O for the optimum point)

GO to 503

511 CALL SCALE (0.0, 2.7, 0.0, 10.0)

(an optional feature of PLOTPT to set limits on scales of X axis and Y axis)

CALL OUTPLT (ie, print the graph just formed)

CALL CAPTN (9, IPROD)

CALL OUTLIN

(an optional feature of PLOTPT to label the axes)

This procedure was used for each of the 17 graphs of output in the thesis.

VI. Sample Problem

The thesis proper contains a detailed development of the program that was written to utilize optimization in budget allocations.

VII. Program Listing

A listing of the computer program written for the thesis forms the second part of Appendix C. A glossary of terms is also included.

GLOSSARY FOR THESIS PROGRAM

Part One - Arrays used to descriptively label axes of graphs in thesis computer output, according to requirements of subroutine PLOTPT (11)

ARRAY	LOCATION IN THESIS	RELATED VARIABLE
IPR	Fig. 3	X(1)
IOCS	Fig. 4	X(2)
ICOCS	Fig. 5	X(2)
IEFF	Fig. 6	X(3)
ICEFF	Fig. 7	X(3)
IDB	Fig. 8	X(4)
ICDB	Fig. 9	X(4)
IROOF	Fig. 10	X(5)
JPROD	Fig. 11	X(6)
ICAP	Fig. 12	X(6)
JLAB	Fig. 13	X(6)
ILAB	Fig. 14	X(6)
JHOUSE	Fig. 15	X(6)
IHOUSE	Fig. 16	X(6)
JSAFE	Fig. 17	X(6)
ISAFE	Fig. 18	X(6)
IOP	Fig. 19	X(6)

Part two - Data cards used to enter utility values of points on utility curves, minimum quantity is 5 points. (11)

LABEL	RELATED INDEPENDENT VARIABLE	DEPENDENT VARIABLE
UPR	X(1)	Good will
UOCS	X(2)	Operating cost savings
UADAPT	X(3)	Adaptability
UDB	X(4)	Noise reduction
UROOF	X(5)	Roof program
UPROD	X(6)	Productivity
UHOUSE	X(6)	Housekeeping
USAFE	X(6)	Safety
ULAB	X(6)	Labour Relations

Part three - Data cards used to enter values of dependent variables corresponding to points listed in Part Two.

LABEL	RELATED INDEPENDENT VARIABLE	DEPENDENT VARIABLE
YOCS	X(2)	Operating cost savings
YADAPT	X(3)	Adaptability
YDB	X(4)	Noise reduction
YPROD	X(6)	Productivity
YSAFE	X(6)	Safety
YLAB	X(6)	Labour relations
YHOUSE	X(6)	Housekeeping

Part Four - Data cards used to enter values of independent variables corresponding to related values of dependent variables in Part Three.

LABEL	INDEPENDENT VARIABLE	RELATED DEPENDENT VARIABLE
XOCS	X(2)	Operating cost savings
XADAPT	X(3)	Adaptability
XDB	X(4)	Noise reduction
XPROD	X(6)	Productivity
		Safety
		Labour Relations
		Housekeeping

Part Five - Data cards used to relate independent variables directly to utility value of Part Two (an exception to the general rule).

LABEL	INDEPENDENT VARIABLE	RELATED DEPENDENT VARIABLE
YPR	X(1)	Good will
YROOF	X(5)	Roof program

Part Six - Miscellaneous Data cards.

LABEL	DESCRIPTION	RELATED DEPENDENT VARIABLES	INDEPENDENT VARIABLE
XOP	Relates operating cost to corresponding points of capital cost	Productivity Safety Labour relations Housekeeping	X(6)

Part Seven - Arrays and data cards used to satisfy requirements of optimization subroutine SEEK 1, as noted in the Optisep Manual. (4)

ARRAY	DATA CARD	DESCRIPTION
RMAX	RMAX	Expected maximum values of independent variables.
RMIN	RMIN	Expected minimum values of independent variables
XSTART	XSTART	Feasible starting values of independent variables
X		Independent variables
PHI		Inequality constraints
PSI		Equality constraints
WORK1		
WORK2		Working arrays to satisfy SEEK 1
WORK3		
WORK4		

Part Eight - Functions, using FTABLE to determine value of dependent variable and utility for a given value of the related independent variable. See program listing for details of use of FTABLE

FUNCTION	INPUT	OUTPUT	RELATED INDEPENDENT VARIABLE
ZPR	Independent value (Good will)	utility	X(1)
COCS	Independent value	dependent value	X(2)
ZOCS	COCS (operating cost savings)	utility	X(2)
CADAPT	Independent value	dependent value	X(3)
ZADAPT	CADAPT (adaptability)	utility	X(3)
CDB	Independent value	dependent value	X(4)
ZDB	CDB (noise reduction)	utility	X(4)

FUNCTION	INPUT	OUTPUT	RELATED INDEPENDENT VARIABLE
ZROOF	Independent value (roof program)	utility	X(5)
CPROD	Independent value	dependent value	X(6)
ZPROD	CPROD (Productivity)	utility	X(6)
CHOUSE	Independent value	dependent value	X(6)
ZHOUSE	CHOUSE (Housekeeping)	utility	X(6)
CSAFE	Independent value	dependent value	X(6)
ZSAFE	CSAFE (Safety)	utility	X(6)
CLAB	Independent value	dependent value	X(6)
ZLAB	CLAB (Labour relations)	utility	X(6)
ZOP	Independent value	operating costs	X(6)

Part Nine - Variables used to describe independent variables.

INDEPENDENT VARIABLE	ASSOCIATED, EQUIVALENT VARIABLES
X(1)	PR, SPR
X(2)	OCS, SOCS
X(3)	ADAPT, SADAPT
X(4)	DB, SDB
X(5)	ROOF, SROOF
X(6)	XP, SPROD

Program Listing

```
USER,T40,
ATTACH,OPTISED.
FTN.
LGET,LIB=OPTISED.
LGO.
      6400 END OF RECORD
      PROGRAM TST (INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
C     COPY ONE
C     ENVIRONMENTAL CONTROL SYSTEMS OPTIMIZATION -.BUDGET ALLOCATIONS
C     USE OF OPTIMIZATION TO DETERMINE BUDGET ALLOCATIONS FOR AN
C     ENGINEERING AND MAINTENANCE DEPARTMENT AT GENERAL MOTORS OF CANADA
C     ST.CATHARINES,ONTARIO,CANADA
C     EMPHASIS IS ON COMPARATIVE VALUE OF SOCIAL,POLITICAL,AND TECHNICAL
C     CONSIDERATIONS INVOLVING SUBJECTIVE EVALUATION
C THE DIMENSION STATEMENTS DEFINE THE ARRAYS USED IN THE PROGRAM.
      DIMENSION IPR(7),IOCS(7),ICOCS(8),ISEE(8),ICEEE(9),IDR(8),
     1ICDR(8),IROOF(6)
      DIMENSION YPROD(8),XPROD(8),UPROD(8),XOP(8)
      DIMENSION IPROD(9),ICAP(10),IOP(7),IHOUSE(9),ILAB(8),ISAFE(7)
      DIMENSION      YOCS(6),UOCS(6),XOCS(6),YADAPT(7),UADAPT(7),
     1XADAPT(7),YDR(11),UDR(11),XDR(11)
      DIMENSION JHOUSE(9),JLAB(8),JSAFE(7)
      DIMENSION YDR(9),UDR(9),UROOF(9),YROOF(9)
      DIMENSION YHOUSE(8),UHOUSE(8),YLAB(8),ULAB(8),YSAFE(8),USAFE(8)
      DIMENSION RMAX(6),RMIN(6),XSTRT(6),X(6),PHI(16),PSI(1),WORK1(6),
     1WORK2(6),WORK3(6),WORK4(6)
C     THE LABELLED COMMON CARDS ARE USED TO TRANSFER DATA TO THE
C     SUBROUTINES FORMING A PART OF THIS PROGRAM.
      COMMON /XA/CHOUSE,ZHOUSE,CSAFE,ZSAFE,CLAB,ZLAB
      COMMON /XB/COSTOT,YHOUSE,UHOUSE,YLAB,ULAB,YSAFE,USAFE
```

```
      COMMON /XW/CADAPT,ZADAPT,COCS,ZOCS,ZOP
      COMMON /XX/UDP,YDP,UPROOF,YPROOF,XADAPT,YADAPT,UADAPT,XOCS,UOCS
      COMMON /XY/YOCS,UPROD,XPROD,YPROD,XDP,UDP,YDP
      COMMON /XU/XP,SPROD,ZPROOF,ZDP,ZPROD,CPROD,CDP,ZDP
      COMMON /XZ/PP,SPP,OCS,SOCS,ADAPT,SADAPT,PP,SDP,PROOF
      COMMON/XP/SPROOF,XOP,PPOP,SSPROP,PPROD
C     THE NEXT TWO CARDS STOP THE PROGRAM IF VARIABLE X(3) DOES NOT
C     WARRANT AN EXPENDITURE.
      PROB=0.6
      IF(PROB.LT.0.5)GO TO 888
C     THESE DATA CARDS ARE USED TO IDENTIFY THE AXES OF THE OUTPUT
C     GRAPHS, AS REQUIRED WHEN USING SUBROUTINE PLOTPT. SEE APPENDIX F
      DATA JHOUSE(1)/10HXAXIS=PER /,JHOUSE(2)/5HCENT /
      DATA JHOUSE(3)/10HIMPROVEMEN/,JHOUSE(4)/5HT IN /
      DATA JHOUSE(5)/10HHOUSEKEEPI/,JHOUSE(6)/3HNG /
      DATA JHOUSE(7)/6HYAXIS /,JHOUSE(8)/8H=UTILITY/
      DATA JHOUSE(9)/10H O=OPTIMUM/
      DATA JLAB(1)/10HXAXIS=PER /,JLAB(2)/5HCENT /
      DATA JLAB(3)/10HREDUCTION /,JLAB(4)/7HLABOUR /
      DATA JLAB(5)/10HCOMPLAINTS/,JLAB(6)/7H YAXIS /
      DATA JLAB(7)/8H=UTILITY /,JLAB(8)/10H O=OPTIMUM/
      DATA JSAFE(1)/10HXAXIS=PER /,JSAFE(2)/5HCENT /
      DATA JSAFE(3)/8HIMPROVED /,JSAFE(4)/7HSAFETY /
      DATA JSAFE(5)/6HYAXIS /,JSAFE(6)/8H=UTILITY/
      DATA JSAFE(7)/10H O=OPTIMUM/
      DATA IPR(1)/6HXAXIS=/,IPR(2)/8HCOST OF /
      DATA IPR(3)/10HGOOD WILL /,IPR(4)/5HCOST /
      DATA IPR(5)/6HYAXIS=/,IPR(6)/7HUTILITY/
      DATA IPR(7)/10H O=OPTIMUM/
      DATA IOCS(1)/10HYAXIS=OPER/,IOCS(2)/10HATING COST/
```

```
DATA IOCS(2)/8H SAVINGS/,IOCS(4)/7H XAXIS=/
DATA IOCS(5)/8HCAPITAL /,IOCS(6)/5HCOST /
DATA IOCS(7)/10H 0=OPTIMUM/
DATA ICOCS(1)/10HYAXIS=DER/,ICOCS(2)/10HATING COST/
DATA ICOCS(3)/8H SAVINGS/,ICOCS(5)/7H XAXIS=/
DATA ICOCS(4)/6H      /
DATA ICOCS(6)/10HRELATED CA/,ICOCS(7)/10HPITAL COST/
DATA ICOCS(8)/10H 0=OPTIMUM/
DATA IEEE(1)/10HXAXIS=PER /,IEEE(2)/5HCENT /
DATA IEEE(3)/10HEFFICIENCY/,IEEE(4)/10H POTENTIAL/
DATA IEEE(5)/6H      /
DATA IEEE(6)/7H YAXIS=/,IEEE(7)/8HUTILITY /
DATA IEEE(8)/10H 0=OPTIMUM/
DATA ICEEE(1)/10HYAXIS=PER /,ICEEE(2)/5HCENT /
DATA ICEEE(3)/10HEFFICIENCY/,ICEEE(4)/10H POTENTIAL/
DATA ICEEE(5)/6H      /
DATA ICEEE(6)/7H XAXIS=/,ICEEE(7)/8HRELATED /
DATA ICEEE(8)/5HCOST /,ICEEE(8)/10H 0=OPTIMUM/
DATA IDB(1)/6HXAXIS=/,IDB(2)/6HNOISE /
DATA IDB(3)/10HREDUCTION /,IDB(4)/4HDBA /
DATA IDB(5)/6H      /
DATA IDB(6)/6HYAXIS=/,IDB(7)/8HUTILITY /
DATA IDB(8)/10H 0=OPTIMUM/
DATA ICDB(1)/6HYAXIS=/,ICDB(2)/6HNOISE /
DATA ICDB(3)/10HREDUCTION /,ICDB(4)/4HDBA /
DATA ICDB(5)/6H      /
DATA ICDB(6)/6HXAXIS=/,ICDB(7)/5HCOST /
DATA ICDB(8)/10H 0=OPTIMUM/
DATA IROOF(1)/10HXAXIS=COST/,IROOF(2)/8H OF ROOF /
DATA IROOF(3)/8HPROGRAM /,IROOF(4)/6HYAXIS=/
```

```
DATA IPROF(5)/8HUTILITY /,IPROF(6)/10H O=OPTIMUM/
DATA IPROD(1)/10HXAXIS=PER /,IPROD(2)/5HCENT /
DATA IPROD(3)/9HINCREASE /,IPROD(4)/3HIN /
DATA IPROD(5)/10HPRODUCTIVI/,IPROD(6)/4HTY /
DATA IPROD(7)/6HYAXIS /
DATA IPROD(8)/8H=UTILITY/,IPROD(9)/10H O=OPTIMUM/
DATA ICAP(1)/10HYAXIS=PER /,ICAP(2)/5HCENT /
DATA ICAP(3)/9HINCREASE /,ICAP(4)/3HIN /
DATA ICAP(5)/10HPRODUCTIVI/,ICAP(6)/3HTY /
DATA ICAP(7)/6HXAXIS /
DATA ICAP(8)/8H=CAPITAL/,ICAP(9)/5H COST/
DATA ICAP(10)/10H O=OPTIMUM/
DATA IOP(1)/10HXAXIS=CAPI/,IOP(2)/10HTAL COST /
DATA IOP(3)/10HYAXIS=PELA/,IOP(4)/10HTED ANNUAL/
DATA IOP(5)/10H OPERATING/,IOP(6)/7H COSTS /
DATA IOP(7)/10H O=OPTIMUM/
DATA IHOUSE(1)/10HXAXIS=CAPI/,IHOUSE(2)/10HTAL COST /
DATA IHOUSE(3)/10HYAXIS=PER /,IHOUSE(4)/5HCENT /
DATA IHOUSE(5)/10HIMPROVEMEN/,IHOUSE(6)/5HT IN /
DATA IHOUSE(7)/10HHOUSEKEEPI/,IHOUSE(8)/3HNG /
DATA IHOUSE(9)/10H O=OPTIMUM/
DATA ILAB(1)/10HXAXIS=CAPI/,ILAB(2)/10HTAL COST /
DATA ILAB(3)/10HYAXIS=PER /,ILAB(4)/5HCENT /
DATA ILAB(5)/10HREDUCTION /,ILAB(6)/7HLABOUR /
DATA ILAB(7)/10HCOMPLAINTS/
DATA ILAB(8)/10H O=OPTIMUM/
DATA ISAFE(1)/10HXAXIS=CAPI/,ISAFE(2)/10HTAL COST /
DATA ISAFE(3)/10HYAXIS=PER /,ISAFE(4)/5HCENT /
DATA ISAFE(5)/9HIMPROVED /,ISAFE(6)/7HSAFETY /
DATA ISAFE(7)/10H O=OPTIMUM/
```

```
THESE DATA CARDS ENTER POINTS FROM THE UTILITY AND COST CURVES.
FUNCTION ETABLE WILL REDEVELOP THE CURVES USING INTERPOLATION.
DATA UDB/0.0,0.2,0.42,0.54,0.75,1.05,1.50,2.10,3.0/
DATA YDB/0.0,50000.0,100000.0,200000.0,300000.0,400000.0,
1450000.0,480000.0,500000.0/
DATA XOCS/50000.0,51500.0,53800.0,55000.0,57200.0,60000.0/
DATA UOCS/0.5,1.75,3.0,3.66,4.25,5.0/
DATA YOCS/100.0,300.0,500.0,600.0,700.0,800.0/
DATA XADART/0.0,20000.0,80000.0,175000.0,350000.0,550000.0,
1000000.0/
DATA UADART/0.0,2.45,4.2,5.6,6.44,6.86,7.0/
DATA YADART/97.0,97.5,98.0,98.5,99.0,99.5,100.0/
DATA XDB/0.0,10000.0,15000.0,20000.0,25000.0,35000.0,40000.0,
160000.0,80000.0,125000.0,335000.0/
DATA UDB/0.0,1.0,2.0,3.0,4.0,5.0,6.0,7.0,8.0,9.0,10.0/
DATA YDB/0.0,1.0,1.5,2.0,2.5,3.25,3.75,4.75,6.0,8.5,15.0/
DATA UBOOF/-5.0,0.,3.2,4.4,5.6,7.0,7.75,7.91,8.0/
DATA YBOOF/0.0,40000.0,50000.0,70000.0,100000.0,150000.0,200000.0,
1250000.0,300000.0/
DATA XOD/0.0,2500.0,5800.0,9500.0,10500.0,11300.0,11500.0,
112000.0/
DATA XBOOD/0.0,17000.0,20000.0,32500.0,34500.0,40500.0,
142500.0,45000.0/
DATA UBOOD/0.0,1.3,2.4,3.5,4.8,8.2,8.8,10.0/
DATA YBOOD/0.0,0.4,0.7,1.0,1.2,2.2,2.3,2.7/
DATA YHOUSE/0.0,5.0,10.0,20.0,30.0,70.0,80.0,100.0/
DATA UHOUSE/0.0,0.1,0.2,0.4,0.6,1.4,1.6,2.0/
DATA YSAFE/0.0,0.8,1.8,3.0,4.2,4.3,4.9,5.0/
DATA USAFE/0.0,0.36,0.36,0.6,0.84,0.86,0.98,1.0/
DATA YLAB/0.0,0.125,0.25,0.5,1.0,3.0,5.5,10.0/
```

```
      DATA ULAB/0.0,0.025,0.05,0.1,0.2,0.6,1.1,2.0/
C     THESE DATA CARDS FULFILL REQUIREMENTS OF OPTISEP. SEE APPENDIX D
      DATA N,IPRINT,IDATA,NCONS,NEQUS,F,G,MAXM,NSHOT,NTEST/6,1,1,16,0,
     1 0.01,0.01,200,2,100/
      DATA RMIN/0.0,50000.0,0.0,0.0,0.0,0.0,0.0,0.0/
      DATA RMAX/500000.0,60000.0,900000.0,335000.0,300000.0,45000.0/
      DATA XSTRT/200000.0,55000.0,200200.0,200000.0,200000.0,35000.0/
C     THE OPTIMIZATION SUBROUTINE IS CALLED AFTER ALL INITIAL DATA
C     HAS BEEN ENTERED.
      CALL SEEK1(N,RMAX,RMIN,NCONS,NEQUS,F,G,XSTRT,NSHOT,NTEST,MAXM,
     1IPRINT,+DATA,X,U,PHI,PSI,WORK1,WORK2,WORK3,WORK4)
      CALL ANSWER(U,X,PHI,PSI,N,NCONS,NEQUS)
C  THE IF STATEMENTS PREVENT PROBLEMS IN THE INTERPOLATION OF DATA
C     BY RESTRICTING THE UPPER AND LOWER LIMITS OF THE VARIABLES.
C     SHOULD ONE OF THE VARIABLES BE ECONOMICALLY INFEASABLE
C     IN THE RANGE OF VALUES FED INTO FUNCTION ETABLE,THE IF STATEMENTS
C     WILL PREVENT MEANINGLESS INTERPOLATION.
      IF(X(1).LT.0.0)X(1)=0.0
      IF(X(1).GT.500000.0)X(1)=500000.0
      IF(X(2).LT.50000.0)X(2)=50000.0
      IF(X(2).GT.60000.0)X(2)=60000.0
      IF(X(3).LT.0.0)X(3)=0.0
      IF(X(3).GT.900000.0)X(3)=900000.0
      IF(X(4).LT.0.0)X(4)=0.0
      IF(X(4).GT.335000.0)X(4)=335000.0
      IF(X(5).LT.0.0)X(5)=0.0
      IF(X(5).GT.300000.0)X(5)=300000.0
      IF(X(6).LT.0.0)X(6)=0.0
      IF(X(6).GT.45000.0)X(6)=45000.0
C     THE NEXT SERIES OF CARDS CODE THE VARIABLES AND DEFINE TERMS
```

```
C     THAT ARE A FUNCTION OF ETABLE OR OTHER APPLICABLE CALCULATIONS.
      DR=X(1)
      SDR=DR
      OCS=X(2)
      SOCS=OCS
      ADAPT=X(3)
      SADAPT=ADAPT
      DR=X(4)
      SDR=DR
      ROOF=X(5)
      SROOF=ROOF
      XR=X(6)
      SPROD=XR
      ZROOF=ETABLE(YROOF,UROOF,SROOF,9)
      ZDR=ETABLE(YDR,UDR,SDR,9)
      CPROD=ETABLE(XPROD,YPROD,SPROD,8)
      ZPROD=ETABLE(YPROD,UPROD,CPROD,8)
      XRET=CPROD*15000.0
      XTOT=XRET*(((1.0+0.05)**10-1.0)/0.05)
      CDR=ETABLE(XDR,YDR,SDR,11)
      ZDR=ETABLE(YDR,UDR,CDR,11)
      CADAPT=ETABLE(XADAPT,YADAPT,SADAPT,7)
      ZADAPT=ETABLE(YADAPT,UADAPT,CADAPT,7)
      COCS=ETABLE(XOCS,YOCS,SOCS,6)
      ZOCS=ETABLE(YOCS,UOCS,COCS,6)
      ZOP=ETABLE(XPROD,XOP,SPROD,8)
      XCOST=SPROD+ZOP*(((1.0+0.05)**10-1.0)/0.05)
      COSTOT=X(1)+X(2)+X(3)+X(4)+X(5)+X(6)
      CHOUSE=ETABLE(XPROD,YHOUSE,SPROD,8)
      ZHOUSE=ETABLE(YHOUSE,UHOUSE,CHOUSE,8)
```

```
      CSAFE=FTABLE(XPROD,YSAFE,SPROD,8)
      ZSAFE=FTABLE(YSAFE,USAFE,CSAFE,9)
      CLAB=FTABLE(XPROD,YLAB,SPROD,8)
      ZLAB=FTABLE(YLAB,ULAB,CLAB,8)
C     THE NEXT TWO CARDS CAUSE OUTPUT STATEMENTS IF VARIABLE X(6)
C     IS ECONOMICALLY UNATTRACTIVE.
      YEARS=(X(6)+ZOP)/XRET
      IF(YEARS.GT.5.0)GO TO 995
C     THE WRITE STATEMENTS PROVIDE THE READABLE FORM OF OUTPUT.
      WRITE(6,100)
      WRITE(6,105)COSTOT
      WRITE(6,191) X(6)
      WRITE(6,200) ZOP
      WRITE(6,210)
      WRITE(6,211)CHOUSE
      WRITE(6,220) CLAB
      WRITE(6,230)
      WRITE(6,231)CSAFE
      WRITE(6,110) X(1)
      WRITE(6,120) COCS
      WRITE(6,130) X(2)
      WRITE(6,140)
      WRITE(6,141)CADAPT
      WRITE(6,150) X(3)
      WRITE(6,160) CDB
      WRITE(6,170) X(4)
      WRITE(6,180) X(5)
      WRITE(6,181)
      WRITE(6,182)CPROD
      WRITE(6,185) XTOT
```

```
      WRITE(6,187)
      WRITE(6,188)YEARS
      WRITE(6,190)
      WRITE(6,192)
100 FORMAT(1H1,*BUDGET ALLOCATIONS DETERMINED BY THIS PROGRAM*///)
105 FORMAT(1X,*TOTAL COST IN DOLLARS*,F10.1/)
110 FORMAT(1X,*ALLOCATION FOR PUBLIC RELATIONS*,F10.1/)
120 FORMAT(1X,*ANNUAL OPERATING COST SAVINGS,DOLLARS*,F10.1/)
130 FORMAT(1X,*COST OF DUST COLLECTORS,MAXIMUM*,F10.1/)
140 FORMAT(1X,*PER CENT EFFICIENCY ATTAINABLE BY EMISSIONCONTROL*/)
141 FORMAT(1X,*EQUIPMENT*,F10.1/)
150 FORMAT(1X,*COST OF PROVISION FOR FUTURE EFFICIENCY LEVEL*,F10.1/)
160 FORMAT(1X,*DROP IN NOISE LEVEL*,F10.1/)
170 FORMAT(1X,*COST OF NOISE REDUCTION,DOLLARS*,F10.1/)
180 FORMAT(1X,*ALLOCATION FOR ROOF IMPROVEMENT,DOLLARS*,F10.1/)
181 FORMAT(1X,*OPTIMUM PRODUCTIVITY OF LIGHT AND COLOUR PROGRAM*/)
182 FORMAT(1X,*EXPRESSED IN PER CENT*,F10.1/)
185 FORMAT(1X,*TOTAL 10 YEAR RETURN,LIGHT AND COLOUR PROGRAM*,F9.1/)
187 FORMAT(1X,*RETURN ON INVESTMENT IN YEARS*/)
188 FORMAT(1X,*FROM LIGHT AND COLOUR PROGRAM*,F10.1/)
190 FORMAT(1X,*USE CURVES PROVIDED TO ROUND OFF BUDGET ALLOCATIONS*/)
191 FORMAT(1X,*CAPITAL COST OF LIGHT AND COLOUR PROGRAM*,F10.1/)
192 FORMAT(1X,*IF REQUIRED*/)
200 FORMAT(1X,*ANNUAL MAINTENANCE COST,IN DOLLARS*,F10.1/)
210 FORMAT(1X,*PER CENT OF MAXIMUM POSSIBLE IMPROVEMENT*/)
211 FORMAT(1X,*IN HOUSEKEEPING*,F10.1/)
220 FORMAT(1X,*PER CENT REDUCTION IN LABOUR COMPLAINTS*,F10.1/)
230 FORMAT(1X,*PER CENT REDUCTION IN MINOR ACCIDENTS,IE,PER CENT*/)
231 FORMAT(1X,*INCREASED SAFETY*,F10.1/)
C     THE REMAINDER OF PROGRAM TST CONTAINS INSTRUCTIONS FOR THE
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C     GRAPHICAL PORTION OF THE PRINTOUT,SUCH AS SCALING,LABELLING THE
      AXES,AND IDENTIFICATION OF THE OPTIMUM POINT.
C     REFER TO THE APPENDIX FOR USE OF SUBROUTINE PLOTPT.
      AX=0.0
      A6=CPROD+0.04
  501 ZPROD=FTABLE(YPROD,UPROD,AX,8)
      IF(AX.GE.CPROD.AND.AX.LE.A6)GO TO 507
      CALL PLOTPT(AX,ZPROD,9)
  508 AX=AX+0.01
      IF(AX.GT.2.7)GO TO 511
      GO TO 501
  507 CALL PLOTPT(AX,ZPROD,35)
      GO TO 508
  511 CALL SCALE(0.0,2.7,0.0,10.0)
      CALL OUTPLT
      CALL CAPTN(9,IPROD)
      CALL OUTLIN
      BX=0.0
      B6=X(6)+250.0
  601 CPROD=FTABLE(XPROD,YPROD,BX,8)
      IF(BX.GE.X(6).AND.BX.LE.B6)GO TO 310
      CALL PLOTPT(BX,CPROD,9)
  315 BX=BX+250.0
      IF(BX.GT.45000.0)GO TO 611
      GO TO 601
  310 CALL PLOTPT(BX,CPROD,35)
      GO TO 315
  611 CALL SCALE(0.0,45000.0,0.0,2.7)
      CALL OUTPLT
      CALL CAPTN(10,ICAP)
```

```
      CALL OUTLIN
      CX=0.0
      C6=X(6)+250.0
700   ZOP=ETABLE(XPROD,XOP,CX,8)
      IF(CX.GE.X(6).AND.CX.LE.C6)GO TO 320
      CALL PLOTPT(CX,ZOP,9)
325   CX=CX+250.0
      IF(CX.GT.45000.0)GO TO 710
      GO TO 700
320   CALL PLOTPT(CX,ZOP,35)
      GO TO 325
710   CALL SCALE(0.0,45000.0,0.0,12000.0)
      CALL OUTPLT
      CALL CAPTN(7,IOP)
      CALL OUTLIN
      FX=0.0
      F6=CHOUSE+4.0
400   ZHOUSE=ETABLE(YHOUSE,UHOUSE,FX,8)
      IF(FX.GE.CHOUSE.AND.FX.LE.F6)GO TO 430
      CALL PLOTPT(FX,ZHOUSE,9)
435   FX=FX+0.5
      IF(FX.GT.100.0)GO TO 410
      GO TO 400
430   CALL PLOTPT(FX,ZHOUSE,35)
      GO TO 435
410   CALL SCALE(0.0,100.0,0.0,2.0)
      CALL OUTPLT
      CALL CAPTN(9,JHOUSE)
      CALL OUTLIN
      DX=0.0
```

```
320 CHOUSE=FTABLE(XPROD,YHOUSE,DX,8)
    IF(DX.GE.X(6).AND.DX.LE.C6)GO TO 330
    CALL PLOTPT(DX,CHOUSE,0)
    DX=DX+250.0
    IF(DX.GT.45000.0)GO TO 810
    GO TO 800
330 CALL PLOTPT(DX,CHOUSE,35)
    GO TO 335
810 CALL SCALE(0.0,45000.0,0.0,100.0)
    CALL OUTPLT
    CALL CAPTN(0,THOUSE)
    CALL OUTLIN
    GX=0.0
    G6=CLAB+0.05
450 ZLAB=FTABLE(YLAB,ULAB,GX,8)
    IF(GX.GE.CLAB.AND.GX.LE.G6)GO TO 455
    CALL PLOTPT(GX,ZLAB,0)
460 GX=GX+0.05
    IF(GX.GT.10.0)GO TO 490
    GO TO 450
455 CALL PLOTPT(GX,ZLAB,35)
    GO TO 460
490 CALL SCALE(0.0,10.0,0.0,2.0)
    CALL OUTPLT
    CALL CAPTN(8,JLAB)
    CALL OUTLIN
    FX=0.0
    C6=X(6)+250.0
900 CLAB=FTABLE(XPROD,YLAB,FX,8)
    IF(FX.GE.X(6).AND.FX.LE.C6)GO TO 340
```

```
      CALL PLOTPT(FX,CLAB,0)
  346 FX=FX+250.0
      IF(FX.GT.45000.0)GO TO 910
      GO TO 900
  346 CALL PLOTPT(FX,CLAB,35)
      GO TO 345
  910 CALL SCALE(0.0,45000.0,0.0,10.0)
      CALL OUTPLT
      CALL CAPTN(8,ILAB)
      CALL OUTLIN
      PX=0.0
      P6=CSAFF+0.05
  951 ZSAFF=FTABLE(YSAFF,USAFF,PX,8)
      IF(PX.GE.CSAFF.AND.PX.LE.P6)GO TO 351
      CALL PLOTPT(PX,ZSAFF,0)
  356 PX=PX+0.05
      IF(PX.GT.5.0)GO TO 961
      GO TO 951
  351 CALL PLOTPT(PX,ZSAFF,35)
      GO TO 356
  961 CALL SCALE(0.0,5.0,0.0,1.0)
      CALL OUTPLT
      CALL CAPTN(7,USAFF)
      CALL OUTLIN
      HX=0.0
      C6=X(6)+250.0
  950 CSAFF=FTABLE(XPROD,YSAFF,HX,8)
      IF(HX.GE.X(6).AND.HX.LE.C6)GO TO 350
      CALL PLOTPT(HX,CSAFF,0)
  355 HX=HX+250.0
```

```
      IF(HX.GT.45000.0)GO TO 960
      GO TO 950
  350 CALL PLOTPT(HX,CSAFE,35)
      GO TO 355
  960 CALL SCALE(0.0,45000.0,0.0,5.0)
      CALL OUTPLT
      CALL CAPTN(7,ISAFE)
      CALL OUTLIN
      QX=0.0
      Q1=X(1)+4000.0
  500 ZPR=FTABLE(YPR,UPR,QX,9)
      IF(QX.GE.X(1).AND.QX.LE.Q1)GO TO 505
      CALL PLOTPT(QX,ZPP,9)
  506 QX=QX+5000.0
      IF(QX.GT.500000.0)GO TO 510
      GO TO 500
  505 CALL PLOTPT(QX,ZPR,35)
      GO TO 506
  510 CALL SCALE(0.0,500000.0,0.0,3.0)
      CALL OUTPLT
      CALL CAPTN(7,IPR)
      CALL OUTLIN
      RX=100.0
      R2=COCS+5.0
  520 ZOCS=FTABLE(YOCS,UOCS,RX,6)
      IF(RX.GE.COCS.AND.RX.LE.R2)GO TO 525
      CALL PLOTPT(RX,ZOCS,9)
  526 RX=RX+5.0
      IF(RX.GT.800.0)GO TO 530
      GO TO 520
```

```
525 CALL PLOTPT(PX,YOCS,35)
    GO TO 526
520 CALL SCALE(100.0,800.0,0.5,5.0)
    CALL OUTPLT
    CALL CAPTN(7,IOCS)
    CALL OUTLIN
    SX=50000.0
    S2=X(2)+100.0
540 COCS=FTABLE(XOCS,YOCS,SX,6)
    IF(SX.GE.X(2).AND.SX.LE.S2)GO TO 545
    CALL PLOTPT(SX,COCS,9)
546 SX=SX+50.0
    IF(SX.GT.60000.0)GO TO 550
    GO TO 540
545 CALL PLOTPT(SX,COCS,35)
    GO TO 546
550 CALL SCALE(50000.0,60000.0,100.0,800.0)
    CALL OUTPLT
    CALL CAPTN(8,IOCS)
    CALL OUTLIN
    TX=97.0
    T3=CADAPT+0.03
560 ZADAPT=FTABLE(YADAPT,UADAPT,TX,7)
    IF(TX.GE.CADAPT.AND.TX.LE.T3)GO TO 565
    CALL PLOTPT(TX,ZADAPT,9)
566 TX=TX+0.03
    IF(TX.GT.100.0)GO TO 570
    GO TO 560
565 CALL PLOTPT(TX,ZADAPT,35)
    GO TO 566
```

```
    CALL SCALE(97.0,100.0,0.0,7.0)
    CALL OUTPLT
    CALL CAPTN(8,IEEE)
    CALL OUTLIN
    YX=0.0
    Y3=X(3)+10000.0
590 CADAPT=FTABLE(XADAPT,YADAPT,YX,7)
    IF(YX.GE.X(3).AND.YX.LE.Y3)GO TO 595
    CALL PLOTPT(YX,CADAPT,9)
596 YX=YX+5000.0
    IF(YX.GT.900000.0)GO TO 590
    GO TO 590
595 CALL PLOTPT(YX,CADAPT,35)
    GO TO 596
600 CALL SCALE(0.0,900000.0,97.0,100.0)
    CALL OUTPLT
    CALL CAPTN(9,ICEEE)
    CALL OUTLIN
    VX=0.0
    V4=CDB+0.2
600 ZDB=FTABLE(YDB,UDB,VX,11)
    IF(VX.GE.CDB.AND.VX.LE.V4)GO TO 605
    CALL PLOTPT(VX,ZDB,9)
606 VX=VX+0.1
    IF(VX.GT.15.0)GO TO 610
    GO TO 600
605 CALL PLOTPT(VX,ZDB,35)
    GO TO 606
610 CALL SCALE(0.0,15.0,0.0,10.0)
    CALL OUTPLT
```

```
      CALL CAPTN(8,IDB)
      CALL OUTLIN
      WX=0.0
      W4=X(4)+5000.0
  620 CDB=FTABLE(XDB,YDB,WX,11)
      IF(WX.GE.X(4).AND.WX.LE.W4)GO TO 625
      CALL PLOTPT(WX,CDB,9)
  626 WX=WX+2000.0
      IF(WX.GT.335000.0)GO TO 630
      GO TO 620
  625 CALL PLOTPT(WX,CDB,35)
      GO TO 626
  630 CALL SCALE(0.0,335000.0,0.0,15.0)
      CALL OUTPLT
      CALL CAPTN(9,ICDB)
      CALL OUTLIN
      XX=0.0
      X5=X(5)+2000.0
  640 ZROOF=FTABLE(YROOF,UROOF,XX,8)
      IF(XX.GE.X(5).AND.XX.LE.X5)GO TO 655
      CALL PLOTPT(XX,ZROOF,9)
  656 XX=XX+2000.0
      IF(XX.GT.200000.0)GO TO 650
      GO TO 640
  655 CALL PLOTPT(XX,ZROOF,35)
      GO TO 656
  650 CALL SCALE(0.0,200000.0,-5.0,8.0)
      CALL OUTPLT
      CALL CAPTN(6,IROOF)
      CALL OUTLIN
```

```
      GO TO 803
  888 WRITE(6,889)
      WRITE(6,890)
      WRITE(6,891)
      WRITE(6,892)
  889 FORMAT(1H1,*VARIABLE X(3) IS NOT VALID*/)
  890 FORMAT(1X,*PROBABILITY OF FUTURE LEGISLATION*/)
  891 FORMAT(1X,*DOES NOT WARRANT A CAPITAL EXPENDITURE*/)
  892 FORMAT(1X,*RERUN PROGRAM WITHOUT X(3)*/)
      GO TO 803
  895 WRITE(6,896)
      WRITE(6,897)
  896 FORMAT(1H1,*RETURN ON INVESTMENT FOR VARIABLE X(6) IS .GT. 5.0
     1YEARS*/)
  897 FORMAT(1X,*RERUN PROGRAM WITHOUT X(5)*/)
  803 STOP
      END
      SUBROUTINE UREAL(X,U)
      DIMENSION XPROD(8)
      DIMENSION XOP(8)
      DIMENSION X(1),YPP(8),UPP(8),YOCS(6),UOCS(6),XOCS(6),
     1YADAPT(7),UADAPT(7),XADAPT(7),YDR(11),UDR(11),XDR(11),YROOF(8),
     1UROOF(8)
      DIMENSION YPROD(8),UPROD(8)
      DIMENSION UHOUSE(8),YHOUSE(8),ULAB(8),YLAB(8),USAFE(8),YSAFE(8)
      COMMON /XA/CHOUSE,ZHOUSE,CSAFE,ZSAFE,CLAB,ZLAB
      COMMON /XB/COSTOT,YHOUSE,UHOUSE,YLAB,ULAB,YSAFE,USAFE,
      COMMON /XW/CADAPT,ZADAPT,COCS,ZOCS,ZOP
      COMMON /XX/UPP,YPP,UROOF,YROOF,XADAPT,YADAPT,UADAPT,XOCS,UOCS
      COMMON /XY/YOCS,UPROD,XPROD,YPROD,XDR,UDR,YDR
```

```
      COMMON /XII/XP,SPROD,ZROOF,ZPR,ZPROD,CPROD,CDR,ZDR
      COMMON /XZ/PR,SPR,OCS,SOCS,ADAPT,SADAPT,DR,SDR,ROOF
      COMMON/XP/SROOF,XOP,PROB,SSPROB,PPROD
      IF(X(1).LT.0.0)X(1)=0.0
      IF(X(1).GT.500000.0)X(1)=500000.0
      IF(X(2).LT.50000.0)X(2)=50000.0
      IF(X(2).GT.60000.0)X(2)=60000.0
      IF(X(3).LT.0.0)X(3)=0.0
      IF(X(3).GT.900000.0)X(3)=900000.0
      IF(X(4).LT.0.0)X(4)=0.0
      IF(X(4).GT.335000.0)X(4)=335000.0
      IF(X(5).LT.0.0)X(5)=0.0
      IF(X(5).GT.300000.0)X(5)=300000.0
      IF(X(6).LT.0.0)X(6)=0.0
      IF(X(6).GT.45000.0)X(6)=45000.0
C     THIS NEXT SERIES OF CARDS MUST BE REPEATED IN SUBROUTINE UREAL,
C     SINCE THEY ARE NOT ASSIGNED OPTIMUM VALUES IN THE MAIN PROGRAM
C     UNTIL THE OPTIMIZATION SUBROUTINE IS CALLED.
      PR=X(1)
      SPR=PR
      OCS=X(2)
      SOCS=OCS
      ADAPT=X(3)
      SADAPT=ADAPT
      DR=X(4)
      SDR=DR
      ROOF=X(5)
      SROOF=ROOF
      XP=X(6)
      SPROD=XP
```

```
      ZROOF=ETABLE(YROOF,UROOF,SROOF,9)
      ZDR=ETABLE(YDR,UDR,SDR,6)
      CPROD=ETABLE(XPROD,YPROD,SPROD,8)
      ZPROD=ETABLE(YPROD,UPROD,CPROD,8)
      CDR=ETABLE(XDR,YDR,SDR,11)
      ZDR=ETABLE(YDR,UDR,CDR,11)
      CADAPT=ETABLE(XADAPT,YADAPT,SADAPT,7)
      ZADAPT=ETABLE(YADAPT,UADAPT,CADAPT,7)
      COCS=ETABLE(XOCS,YOCS,SOCS,6)
      ZOCS=ETABLE(YOCS,UOCS,COCS,6)
      ZOP=ETABLE(XPROD,XOP,SPROD,8)
      XCOST=SPROD+ZOP*(((1.0+0.05)**10-1.0)/0.05)
      XRET=CPROD*15000.0
      CLAB=ETABLE(XPROD,YLAB,SPROD,8)
      ZLAB=ETABLE(YLAB,ULAB,CLAB,8)
      CSAFE=ETABLE(XPROD,YSAFE,SPROD,8)
      ZSAFE=ETABLE(YSAFE,USAFE,CSAFE,8)
      CHOUSE=ETABLE(XPROD,YHOUSE,SPROD,8)
      ZHOUSE=ETABLE(YHOUSE,UHOUSE,CHOUSE,8)
      COSTOT=X(1)+X(2)+X(3)+X(4)+X(5)+X(6)
C     THE OPTIMIZATION EXPRESSION IS INCLUDED AT THIS POINT.
      U=-(ZDR+ZOCS+ZADAPT+ZDR+ZROOF+ZPROD+ZHOUSE+ZSAFE+ZLAB)
      RETURN
      END
      FUNCTION ETABLE(VAR,FUNC,XX,M)
C  VAR=DISCRETE TABULAR VALUES OF THE VARIABLE
C  FUNC=DISCRETE TABULAR VALUES OF THE FUNCTION
C  XX=GIVEN VALUE OF THE VARIABLE
C  M=NUMBER OF STATIONS OR TABLE VALUES
C  ETABLE=INTERPOLATED VALUE OF THE FUNCTION CORRESPONDING TO XX
```

```
      DIMENSION VAR(1),FUNC(1)
      NEND=N-1
      DO 10 I=1,NEND
      INT=I
      IF(XX.GT.VAR(I).AND.XX.LE.VAR(I+1))GO TO 11
   10 CONTINUE
   11 FTABLE=FUNC(INT)+(XX-VAR(INT))*(FUNC(INT+1)-FUNC(INT))/(VAR(INT+1)
     1-VAR(INT))
      RETURN
      END
      SUBROUTINE CONST(X,NCONS,PHI)
      DIMENSION XADAPT(7),XDB(11),PHI(1),YROOF(8),UROOF(8)
      DIMENSION YADAPT(7),UADAPT(7),YPP(9),UPP(9),YDB(11),UDB(11)
      DIMENSION YPROD(8),XPROD(8),UPROD(8),XOP(8)
      DIMENSION X(1),YOCS(6),UOCS(6),XOCS(6)
      COMMON /XA/CHOUSE,ZHOUSE,CSAFE,ZSAFE,CLAB,ZLAB
      COMMON /XB/COSTOT,YHOUSE,UHOUSE,YLAB,ULAB,YSAFE,USAFE
      COMMON /XW/CADAPT,ZADAPT,COCS,ZOCS,ZOP
      COMMON /XX/UPP,YPP,UROOF,YROOF,XADAPT,YADAPT,UADAPT,XOCS,UOCS
      COMMON /XY/YOCS,UPROD,XPROD,YPROD,XDB,UDB,YDB
      COMMON /XU/XP,SPROD,ZROOF,ZPP,ZPROD,CPROD,CDB,ZDB
      COMMON /XZ/PP,SPP,OCS,SOCS,ADAPT,SADAPT,DB,SDB,ROOF
      COMMON/XP/SROOF,XOP,PROB,SSPROB,PPROD
      IF(X(1).LT.0.0)X(1)=0.0
      IF(X(1).GT.500000.0)X(1)=500000.0
      IF(X(2).LT.50000.0)X(2)=50000.0
      IF(X(2).GT.60000.0)X(2)=60000.0
      IF(X(3).LT.0.0)X(3)=0.0
      IF(X(3).GT.900000.0)X(3)=900000.0
      IF(X(4).LT.0.0)X(4)=0.0
```

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      IF(X(4).GT.335000.0)X(4)=335000.0
      IF(X(6).LT.0.0)X(6)=0.0
      IF(X(5).GT.300000.0)X(5)=300000.0
      IF(X(6).LT.0.0)X(6)=0.0
      IF(X(7).GT.45000.0)X(6)=45000.0
      PHI(1)=X(1)
      PHI(2)=500000.0-X(1)
      PHI(3)=X(2)-50000.0
      PHI(4)=60000.0-X(2)
      PHI(5)=X(3)
      PHI(6)=900000.0-X(3)
      PHI(7)=X(4)
      PHI(8)=335000.0-X(4)
      PHI(9)=X(5)
      PHI(10)=300000.0-X(5)
      COST=(X(2)-50000.0)*((0.09*1.09**10)/(1.09**10-1.0))
      SAVE=COST*10.0
      DEN=SAVE-COST
      PHI(13)=DEN
      PHI(11)=X(6)-0.0
      PHI(12)=45000.0-X(6)
C     DETERMINE RETURN ON INVESTMENT IN TERMS OF DOLLAR VALUE OF
C     INCREASED PRODUCTIVITY (INFLATION RATE 5 PER CENT)
C     BASED ON RETURN IN DOLLARS OVER A 10 YEAR PERIOD
C     CURRENT RETURN IS $ 15,000 FOR 1 PER CENT INCREASE IN PRODUCTIVITY
C     PHI(14) OR CONSTRAINT 14 REFERS TO INDEPENDENT VARIABLE X(6).
      XRET=CPROD*15000.0
C     CALCULATE TOTAL 10 YEAR RETURN.
      XTOT=XRET*(((1.0+0.05)**10-1.0)/0.05)
C     DETERMINE CAPITAL COSTS AND OPERATING COSTS FOR 10 YEARS
```

```
C     USE INCREASED COST FACTOR (INTEREST) OF 5 PER CENT
      XCOST= X(6)+ZOP*(((1.0+0.05)**10-1.0)/0.05)
      PHI(14)=XTOT-XCOST
C     THE LAST TWO CONSTRAINTS FORMULATE THE UPPER LIMIT OF THE
C     PROPOSED BUDGET.   TOTAL COST=COSTOT
      PHI(15)=1000000.0-COSTOT
      PHI(16)=COSTOT-999000.0
      RETURN
      END
      6400 END OF RECORD
           END OF FILE
```

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