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# FOREIGN TECHNOLOGY DIVISION

"HOW TO INCREASE SPEED AND SAVINGS?"
SIMPLE INTRODUCTION TO THE TECHNIQUE OF "OPTIMIZATION"

By

Jin Fan

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# EDITED TRANSLATION

FTD-ID(RS)T-0993-79          25 July 1979

MICROFICHE NR: FTD-79-C-000975

CSB78221658

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English Pages: 8

Source: Hang K'ung Chih Shih, Nr. 4, 1978, pp. 33-35

Country of Origin: China
Translated by: SCITRAN
F33657-78-D-0619
Requester: FTD/PHE
Approved for public release; distribution unlimited.

"How to Increase Speed and Savings?"

A Simple Introduction to the Technique of "Optimization"

by Jin Fan

In designing an airplane, how can weight be minimized within the requirements of adequate safety and reliability? In designing a rocket, how can maximum range be achieved within the fixed condition of take-off weight? The technique of "optimization" can be borrowed to help solve problems of this kind.

The technique of "optimization" is a new realm developed by the techniques of modern science: its role in specialized, theoretical research and specialized technical applications has appeared in the last few decades and particularly in the last ten or so years. This development cannot be separated from the practical requirements of the development of science and technology and the development and wide-spread use of computer technology.

## THE ORIGIN OF THE CONCEPT OF "OPTIMIZATION"

One could say that the original concept of "optimization" existed very early. For example, using a string of a given length, what kind of shape should it be laid down in so that it encompasses the largest area? Men had already answered this question even in ancient times: use the string to encompass a circle, and it will enclose a larger area than any other shape. However, a theoretical investigation and solution had to wait until the eighteenth century.

In 1696 Johannes Bernoulli published a letter calling the attention of mathematicians to the so-called problem of the fastest slope and fastest line of descent. The problem states: given two points A and B, not defining a horizontal line, what line can be followed between the two points in the shortest time (see figure 1). At first sight, it it seems that a straight-line distance is shortest and, therefore, would require the shortest time. However, it is not so. In the light of later research, we know that the fastest line of descent is a circular line. This is because, although the line is longer, an object acquires more speed on the relatively longer line segment. From the investigations of men into the problems of fastest line of descent and the circumference of a circle, which have been mentioned above, came the study of variation. And the methods of the study of variation have very important uses in solving all kinds of "optimization" problems.

In Chinese history, the story is told of the horserace between Chi Wang and Tyan Ji. One day, Chi Wang wanted Tyan Ji to have a horserace with him, and he stipulated that each of them would choose one horse from among their good horses, mediocre horses and bad horses. Moreover, he also stipulated that, if anyone's horse lost, the loser must pay a thousand pieces of gold and, if a horse won, the winner would get a thousand pieces of gold. Because Chi Wang's good, mediocre and bad horses were all stronger than Tyan Ji's horses in the corresponding classes, it seemed that Chi Wang would win three thousand pieces of gold. However, Tyan Ji's advisor, Swun Bin, put him in mind of a strategy. If Tyan Ji used his bad horse against Chi Wang's good horse, used his mediocre horse against Chi Wang's bad horse and used his good horse against Chi Wang's mediocre horse, then, the result of the race would be that Tyan Ji's good and mediocre horses would both win, and he would win a thousand pieces of gold. This is a simple example of an "optimization" problem.

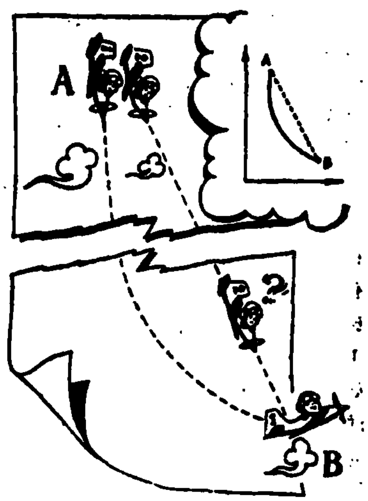


Fig 1. Fastest Line of Descent

From the example above, we can understand the origin of the original concept of "optimization" and its development. What it is necessary to point out is that, only if a given society has practical needs is it possible to promote the speedy development of that society. During the Second World War, from the problem of the organization of production, the problem of material coordination and shipment, the problem of the disposition of troops, the problem of aerial reconnaissance and submarines, from these practical requirements, came theories of planning, theories of counter-measures and so on. Radar technology was discovered and began to be applied during the period of the Second World War. It was a huge technological step forward over the old method of depending on hearing the sound of engines in order to fix the position of aircraft. This step forward caused the opportunities for intercepting enemy bombers to go up ten fold, moreover, "optimization" workers, in applying this new technique, raised it again to twenty fold. This makes clear that the application of and research into "optimization" techniques have real significance. Particularly in the last ten years or so, the development of automatic control technology and aviation technology has given rise to demands for high precision, high reliability and high speed and consequently to a set of "optimization" problems. At the same time, due to the development of computer technology, these problems could not only be described in terms of mathematics, but also became susceptible to practical solutions. To say it in reverse, the wide variety of everyday applications of computer technology caused men to be able to apply "optimization" techniques to solving an even greater variety of practical problems, to obtain even better economic and technological results and, because of this, to attract the attention and esteem of people to an ever-increasing degree.

"Optimum" means good; good and bad can only be talked about in terms of their mutual opposition; existence and development only exist in terms of mutual comparisons. What is called "optimization" is only the expectation that, under specific conditions, good objectives actually can be reached. What we normally talk about as good and bad is only a qualitative concept; investigate to any degree you like, there still is no clear standard. Because of this, during research into concrete problems, it is not enough to simply talk about good and bad; it is still necessary to have a specific standard of measure. If we can set up a standard of good and bad based on the requirements of practical problems, and beyond this, use exact mathematical formulas to express the various types of conditions, then one could turn this kind of practical problem into a mathematical question for purposes of research. This is the mathematical implication of "optimization".

## SELECTING THE OPTIMUM PLAN

Below, we present a simple example. Suppose we want to manufacture a certain kind of machine tool, and each machine tool requires three types of shafts (A, B and C) which have different measurements; the specifications are given below:

| Type | Specification (in meters) | No. needed per machine tool |
|---|---|---|
| A | 2.9 | 1 |
| B | 2.1 | 1 |
| C | 1.5 | 1 |

These shafts must use the same type of steel rod for finishing; its length is 7.4 meters. The current plan requires the manufacture of 100 machine tools. We must ask: at a minimum how many steel rods must be used to finish into the steel shafts?

This is a question of choosing the most economical plan. If one chooses a workable plan, the problem is not difficult to solve, relying on experience. For example, taking 50 steel rods and cutting each one into two A-type rods and one C-type rod, one would get a hundred A-type rods and 50 C-type rods: taking another 25 steel rods and cutting each into two C-type rods and two B-type rods, one would get 50 C-type rods and 50 B-type rods. Now, we are still short 50 B-type rods and still need 17 steel rods. In this way, we would use 92 rods of raw material all together. This, of course, is a workable plan. However, is it the most economical plan? We still cannot answer that. If it is not, can we find the most economical plan through mathematical description?

In order to do this, we arrange the various cutting methods in the table below:

| Cutting Method No. | No. of 2.9m Rods (A) | No. of 2.1m Rods (B) | No. of 1.5m Rods (C) | Excess (m) |
|---|---|---|---|---|
| 1 | 2 | 0 | 1 | 0.1 |
| 2 | 1 | 2 | 0 | 0.3 |
| 3 | 1 | 0 | 3 | 0 |
| 4 | 0 | 2 | 2 | 0.2 |
| 5 | 0 | 3 | 0 | 1.1 |
| 6 | 1 | 1 | 1 | 0.9 |

Looking at the table, using plans 5 and 6 produces a relatively large amount of excess material; this is unsatisfactory. Using plans 1 and 3 to cut produces relatively little excess material and is more satisfactory, however, these plans do not meet the requirement because they do not produce any 2.1 meter shafts. Because of this, we must simultaneously test plans 2 and 4 and how they satisfy the requirement. Now our question is: using plans 1, 2, 3 and 4 how many rods will each plan use to produce 100 sets of shafts and still minimize the total of wasted rods of raw material?

If we suppose that the number of rods to be cut using plan 1 is $X_1$, the number of rods to be cut using plan 2 is $X_2$, the number of rods to be cut using plan 3 is $X_3$ and the number of rods to be cut using plan 4 is $X_4$, we can then say that the total number of each of the A, B and C-types of shafts is:

No. of A-type shafts$=2X_1+X_2+X_3$

No. of B-type shafts$=2X_2+2X_4$

No. of C-type shafts$=X_1+3X_3+2X_4$

In order to match up the types of shafts to make 100 sets one can arrive at the table of mathematical formulas below:

$$\left.\begin{aligned} 2X_1+X_2+X_3&=100\\ 2X_2+2X_4&=100\\ X_1+3X_3+2X_4&=100 \end{aligned}\right\}(1)$$

$$X_i \geqslant 0,\ i=1、2、3、4.$$

The total number of shafts expended is:

$$f(X_1、X_2、X_3、X_4)=X_1+X_2+X_3+X_4 \qquad (2)$$

Our problem is then to derive the smallest value of (2) given the conditions in (1). We designate (2) to be the target function, designate (1) to be the restricting conditions, designate $X_i$ the design change measure. This is a problem in determining extreme values and can be called an "optimization" problem. Solving the problem we get the following answers

$$X_1=20,\ X_2=40,\ X_3=20,\ X_4=10;\ X_1=10,\ X_2=50,\ X_3=30,\ X_4=0;\ 或\ \text{or} \cdots\cdots$$

This way one will expend 90 steel rods and get exactly 100 sets. This indeed is the single most economical method.

From the discussion above one can see that, if this kind of simple problem does not have a single solution and if one depends only on the "trial and error" method it will be very difficult to find the optimum plan and difficult to recognize it as such if one does find it. However, after going through this kind of mathematical treatment, it is then very easy to find the optimum plan.

In quite a few problems which arise in engineering technology, for example, we want to design a multi-stage rocket and must attain a pre-determined speed with minimum fuel consumption; perhaps, under an assumption of a given total weight, one must correctly distribute weight among the various stages in order to obtain maximum range; or, to give another example, we are designing an airplane and require minimum weight within the requirements of adequate safety and reliability; or, in problems of interception in space and orbital changes in space, one needs minimum times, etc. These types of questions are, of course, much more complex than the problem of saving raw material mentioned above, so, depending on experience and a "trial and error" method would, generally speaking, only produce a barely workable method even at the expense of a great deal of work. If, after we handle problems in accordance with the principles and methods of "optimization," we advance toward good goals always carefully examining the possibilities of every situation according to some strategy, and avoid aimlessness in this way, we will certainly reach goals very quickly. Having computers, we can use them to automatically search out the optimum plan.

## OPTIMUM DESIGN

Following along with the development of science and technology, each science and technological realm has produced large numbers of optimization problems. The common types of these problems have many aspects and each of these types has been organized into a separate branch of study according to the special nature of each of the types of questions. Looking from the point of view of applied engineering technology, we can generally identify three types of problems: one type is process control problems and optimum control problems; one type is problems of selecting optimum plans referred to as optimum design; the third type is experimentation/testing problems and problems relating to the optimization of experimentation/testing.

Here, we will introduce again the general situation regarding optimum design.

We always hope to be able to select a relatively optimum plan when carrying out any piece of engineering design. However, concerning systems with relatively complex designs, following traditional design methods, designers often have difficulty realizing their own expectations. For example, suppose we want to design an airplane according to traditional design methods, first, from the experience of the designers, choose initial values for the various design parameters and form a preliminary plan, refigure the various capabilities of this plan and compare them to the design requirements. Generally speaking, one estimate will certainly not allow one to adequately satisfy requirements; since this is so, one then needs to correct certain parameters and form a second plan; repeating this process through several refinements, one arrives at a new plan which satisfies requirements and then stops. However, with a change in design parameters, one needs a new estimate of weight, propulsion capabilities, aerodynamic characteristics and, on the basis of these, a new figuring of the aircraft capabilities; because of this, there is a great deal of work involved in figuring a new plan. Because of this, designers, when they are designing, can perform only a very few checks; generally, they can only readjust a few parameters (for example, power to weight ratio, wing loading, aspect ratio, rear deflection, etc.). At the same time, practical design work still requires going through testing in order to validate a design; for example, the wind tunnel test in the project design phase. Due to the expense and time involved in testing, it is only possible to allow a very small number of tests to be made. Designs done according to this kind of design process are usually only "workable methods" which simply satisfy requirements; they are not optimum methods.

By using computers one can figure out a large number of possible methods of various types in a very short time allowing one to choose the optimum method from among them; this is manifestly a great step forward when compared to the "trial and error" method which depends on experience of a given level, even including subjective personal decisions, and which can only give careful consideration to a small number of factors. However, we must point out that, while we can use computers to carry out design work, the method of calculating all the possible plans still is not the best one. That being the case, can we think of a way of figuring out the optimum method without figuring out all the possible methods? This is possible. Optimization theory and methods, particularly non-linear programing methods, offer a foundation for optimum computer design. In the way we have discussed before, we will take a practical problem and turn it into a mathematical problem in optimization, set up a mathematical model for optimization and establish a standard for distinguishing between good and bad. After figuring out each method, we can carry out a comparison with a previous method, then, figuring out the methods which have the most future use according to a given guideline, we can eliminate the very numerous methods which have no future use; in this way we can find the optimum method without having to figure out all the possible methods; this is a process of optimum selection. A process of this kind we call optimum design.

According to reports from abroad, the American Boeing Company used a type of optimization program to carry out optimization of the pay-load plan of a high-speed transport aircraft with the result that the passenger pay-load increased from 192 persons to 253 persons, an increase of 31 percent.

At present, in the field of construction, optimum design is developing by leaps and bounds. In simple structures, optimum design can reduce materials 7% compared with ordinary designs; in somewhat more complex structures, it can save 20% on materials used; and, in relatively complex structures, it can reduce weight by 40%. For example, according to literary reports, non-linear programming methods applied to the design of aircraft wings can reduce weight by 35 percent. Optimization of structural designs, except for the most light-weight designs, can stand up to the most rigorous structural inspection. A structure is often composed of numerous elements; the functions of these different elements in the structure as a whole are not the same; the influence of their failure on the structure as a whole is not the same; because of this, the probability of failure of the various elements can be fixed at different values. This is appropriately reflected in the choosing of relatively high strength values for secondary elements and relatively low strength values for main elements (sic); in this way, a design can be more economical than it would have been if uniform strength values had been used throughout, and safety is also increased.

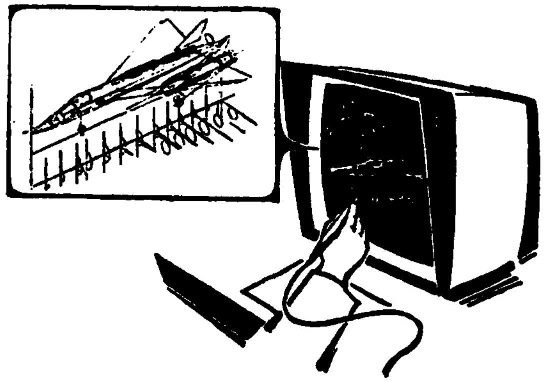

Fig 2. Using Light Pen to Correct Graphic Computer Display

We can see that the application of optimum design by computer has many advantages. However, it is worthwhile to point out that, although manual design has its shortcomings, it also has its strong points. Because people have long practical experience, they can make timely decisions during the design process, correct designs, etc. ; this is something computers cannot do. Naturally, we can ask: can we not put the speed of computers and the experience of people together? Present technological levels already offer this kind of capability. At present, it is already possible to utilize the existing automatic print-out and graphic displays of computers in such a way as to give a physical representation of a design plan in the computer; moreover, it is also possible to use a "light pen" to make corrections on the graphic display directly and in a timely manner. (See Figure 2) Going along with this, while the computer is running, designers can interrupt calculations from time to time, depending on the situation, correct the input program and change the analytic process in such a way that the experience of men and the speed of computers are brought together very well, in such a way that the selection of an optimum plan is the result of the direct, mutual cooperation of man and computer. This not only avoids unnecessary calculations and raises efficiency but, at the same time, due to timely supervision of mutual efforts, we, then, have the possibility of understanding better the internal connections between problems during the analytic process; moreover, we have a better grasp of how to use those effective special patterns to avoid aimlessness in design activity. This kind of design process we may call machine-assisted design. This type of effective design method will find wide application in the design departments of the aerospace industry.

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