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______________海关：

由我校 许庆瑞 （教授、副教授、讲师）撰写的关于 Application of System Dynamics in R & D Project Planning and Policy Analysis 系统动态学在科技项目规划中的应用 的科学研究学术论文中、英文 壹 篇，共 25 页。经专业审查，符合国务院国发〔1981〕165号文件关于"科学技术保密条例"的第十一条。同意寄往 Jorgen Randers, Norweigian School of Management Hans Burums vei 30, 1341 Bekkestua, Norway 参加 1984年系统动态学国际学术会议，请放行。

此 致

敬 礼！

浙江大学学术委员会

一九八四年四月廿日

APPLICATIONS OF SYSTEM DYNAMICS IN R&D PROJECT PLANNING AND POLICY ANALYSIS

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ABSTRACTS

Emphasis on economic effectiveness and benefit in our country results in the emphasis of economic analysis in project planning and evaluation during recent several years.

The weakness of existing approaches in project planning and analysis to certain extent is lack of dynamic in nature.

The effectiveness of system dynamic approach in project planning and analysis is not only due to its systematic and dynamic analysis, but also due to its value in quantitative analysis and policy analysis. The idea and model of R&D project planning is useful in solving above-mentioned problems.

The learning curve nature in development activities.

Adoption of task-performance coefficient as a factor in R&D system dynamics modeling.

The labor psychological factor in our country and its characteristics in formulation of system dynamics simulation model.

R&D cost as a major element is involved in the model.

Policy analysis through simulation running is an important basis for decision-making in R&D project planning.

In 1950s, our country began to emphasize the economic analysis of research and development projects in the large scope of economic construction. Significant economic benefits were achieved. Therefore, it played a large part in achieving better benefits of investment and better economic effects both on the society as a whole and on enterprises and in speeding up the development of our socialist construction.

THE ECONOMIC BENEFIT OF SOCIALISM FIRST OF ALL COMES FROM PLANNING

The experience of economic construction in the First Five-Year Plan and the early three years of the Second Five-Year Plan period in our country proved that stressing the economic benefits was a crucial principle, especially to a developing country. Capital for investment is the scarcest resource in a developing country. This is also true to our nation. There are many ways to solve this problem. As to our nation, we must rely heavily on self-reliance. Of course, it does not mean that we have to shut the door against every other nation. We can communicate with developed countries in science, technology and economy, including the use of technology and capital from foreign country. However, the main source of capital for construction is domestic ones. Since there is a vast domestic market in our nation, it becomes an important factor in ensuring for our country steady increase of economy without being interrupted by the economic crises throughout the world.

In order to base ourselves on home when building up the capital for the socialist economic construction in our nation we should stress the economic benefit, bring economic activities on the course of achieving better economic results and make economic evaluation of such projects as research, development and planning ones. Only when focusing on it, can we have correct and effective decision-making.

Since our country is a socialist one, the primary and fundamental characteristic of a socialist economy should be a planned system. There should be a overall national economic plan, in the light of which science, technology, production, transportation and so on are smoothly managed and integrated.

The economic results of work performance depends, to a great extent, on the quality of planning and wether the planning itself implements the guideline of achieving better economic results. Moreover, China being a socialist nation, all plans, ranging from enormous macro-plans such as of national economy to small micro-plans such as of enterprises as well as of project programs, should carry out the guideline of achieving better economic effects. In the process of planning, the economic evaluation should be made. Similarly, in making plans of science and technology, including R&D plans and the plans of technology progress, we should undoubtly stress technological and economic evaluation, striving for better economic results and make every effort to achieve the best economic results with the least manpower and the fewest material resources.

ECONOMIC EVALUATION OF A R&D PROJECT AND ITS PLANNING

In a quite long period we followed the theory and method of technological and economic analysis introduced from the Soviet Union. There were some serious shortcomings in this approach, the main one of which was the lack of overall dynamic analysis. It was related to the limitation of the theories and methods of management and economic analysis in that period

(1950s). It seemed to have seriously damaged the planning, especially to R&D planning. Because the crux of planning lay in overall and comprehensive balance and in long and middle range prediction for the future, failing to analyse the problems comprehensively and lacking the prediction can hardly assure the correctness and effectiveness of planning and decision-making. R&D planning was characterized as long-range one. Any approach without involving dynamic analysis for long-range appeared unable to survive. Consequently, its effectiveness would be drastically reduced.

Another shortcoming of the existing approach was its inability of utilizing modern approaches and means effectively, especially its inability of applying computer-aided decision-making techniques effectively. As a result, it cannot compare a large number of schemes and employ quantitative techniques to analyse all alternative policies in order to seek out the optimum decision as a basis for policy making.

System dynamics displayed significant superiority in solving above-mentioned problems. It can analyse R&D projects systematically, dynamically and quantitatively. In addition, it can analyse R&D projects and select the best ones, when multi-indices exist and a lot of projects are compared simultanously.

SYSTEM DYNAMIC MODELS OF R&D PROJECT PLANNING

It is necessary to distinguish the research activities

from development ones and make plans and establish system dynamic models according to their own distinctions. The practice of our nation has indicated that the development activities are more determinate and are able to formulate task norm. Thus, quantitative techniques and system dynamic models can be effectively employed when particular planning of development projects is made.

This article employed the R&D model set up by Edward Roberts as a basis to discuss the problems and relate the experience of our nation to probe into the problem of R&D modeling as well as decision-making in this area.

Following problems are worth clarifing:

* The learning curve effect in R&D project.
* Motivation and its effectiveness in R&D project.
* The attitude and psychological factor in R&D project completion.
* Use of comprehensive index-system for R&D project evaluation and choice.

The model to be presented consists of more than fourty equations (see appendix). It is composed of four parts: (1) Progress; (2) Productivity; (3) Manpower; (4) Change in Cost. The first part is involved in the real progress rate, level of cumulative real progress etc. This part is similar to the work done by Professor Ed. Roberts. The 2nd part is concerned with productivity, two characteristics are appeárently appeared in our country. One is the learning curve effect in development work. Development work, including machine design, is different from those of research work, it is an engineering work, a combination of uncertainty and routinized work with much more certainty than research work. According to the practice of some machine-tool manufacturing firms in our country, a learning curve effect could be perceived, which is to some extent similar to the producion one. (See Fig.1)

Fig.1 is a curve concerning design time of machine tool components (parts) over time. For instance, in a machine-tool company, which initiated to design & produce grinding machine in 1953, the average design time of one equavalent component of the machine tool was changing over years.

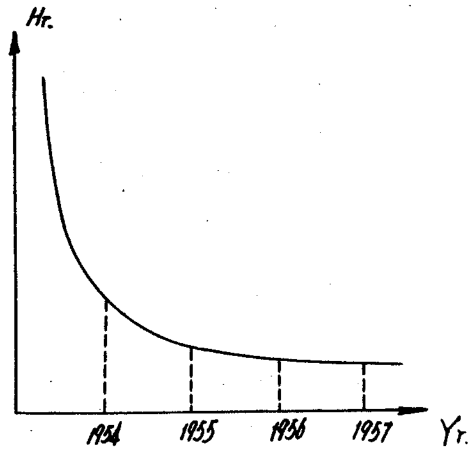


Fig. 1

year	design time required
1953	14 hours or more
1957	11 hours

This factory develops more than ten kinds of new grinding machine each year, which offers the designers an opportunity to raise their skill and productivity. By the time this machine

tool factory also gives out a reward system for engineer and designers.

According to this learning curve effect in development, it is suitable to add "Norm Performance Factor" (NPF), by use of CLIP Function in the "Productivity" part of our model as follows.

PROD.K=(PM.K)(PRODN)(NPF.K)

PRODN=2

PM.K=TABLE(TPR, RFSC.K, 0, 2, .25)

TPM=.6/.65/.75/.85/1/1.3/1.5/1.6/1.45/1/.8

NPF.K=TABLE(TNPF, TIME.K, 0, 72, 6)

TNPF=.6/.7/.8/.85/.9/.95/1/1.02/1.04/1.055/1.065/1.075/1.082

here, NPF---Norm Performance Factor
(skill from Practice over time)
CLIP---Clip Function
PM---Productivity Multiplier
PRODN---Productivity, Normal(Job unit/man-month)
TPM---Table Productivity Multiplier
RFSC---Ratio of Forecast to Scheduled Completion Dates

In 1950s, many of our machine-building manufactures initiate a reward system in R&D Dept by use of norms (or work standard) for developing work and design work. A variety of norms is identified to different kinds of jobs, such as design of machine components, design of process, design of tool used in plant for producing new components and so on. The norm is also classified according to the difficulties and novelty of the machine. These norms are periodically reviewed and modified by use of statistical and empirical data. A reward system was well designed to fit the norm-performance system of designing and developing work.

In these several years, Economical Responsibility System has been erected and widely adopted in our industry. And, the abovementioned norm-performance-reward system is integrated with the economical responsibility system, and plays a great role in raising the productivity of R&D activities in our factory.

For instance, according to the practice of Shanghai Machine-Tool Company, since the norm-performance-reward system was integrated with the economical responsibility system, the performance of norm(work standard) for design work is 15-20% higher than before, in other words, the design time of a component is reduced by 15-20% than the original.

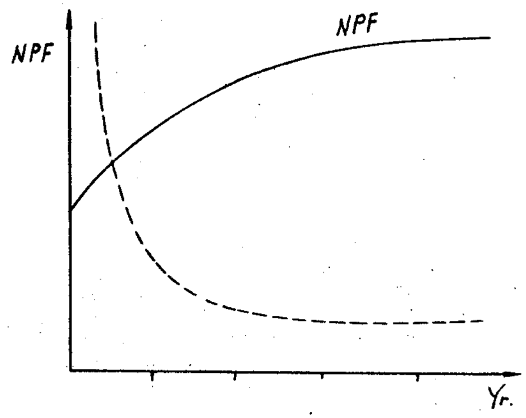


Fig. 2 Norm-Performance Factor Curve

Based on the learning curve effect, we can draw the curve of Norm-Performance Factor as shown in Fig.2

Corresponding to the Norm-Performance Factor curve, we may draw out a series of norm-performance coefficients as below:

TNPF=.6/.7/.8/.85/.9/1/1.02/1.04/1.055/1.065/1.075/1.082

Certainly, these series of coefficient would influence to behavior of productivity as well as that of real progress of the project.

Another important character having to be discussed here is about the productivity multiplier (PM). As known, the actual productivity of the average engineer/scientists working on the R&D job is not merely influenced by the increasing skillfulness and sophistication in the appearance of the learning curve, but also influenced by the attitude of the engineer/scientists and the motivation, as well as the pressure on the schedule. All these factors impact the productivity through the productivity multiplier. In this side, the social and psychological aspects as well as the culture play a great role. The people of our nation is diligent and will not be frightened by any difficulty. Our motto is "The more difficulty there is, the more action we will take" "Difficulties can never scare us". Especially, under the pressure of schedule and urgent mission, usually the engineer and scientist can perform the work standard over 50-80%, sometimes 100% or more. Due to all of these, the productivity multiplier curve would be in different manner from the western style in average (see Fig. 3).

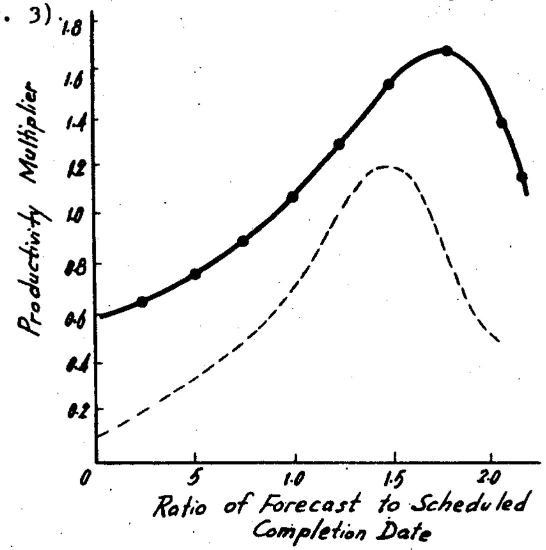


Fig. 3

Corresponding to the PM Curve in Fig.3, we can obtain a series of PM data as follows:

TPM=.6/.65/.75/.85/1/1.3/1.5/1.6/1.45/1/.8

For the sake of taking a whole view in reviewing and assessing a R&D project planning decision, it is necessary to include some indices in R&D expense dimension. Accordingly, a fourth part of cost is arranged in the model as below:

CMEN.K=CMEN.J+(DT)(MEN.J)

CMEN=0

CCOST.K=WEPMM*CMEN.K

WEPMM=1980 YUANS

CMEN---Cumulative Men on Project (Man-Month)

CCOST---Cumulative Cost (Yuans)

WEPMM---Wage Plus Expenses per Man-Month (Yuans)

Here, only gives the idea, a more complete part of cost is needed to be developed further.

POLICY ANALYSIS---SYSTEM BEHAVIOR

The model presented here is only an approximation of the complex system of research and development projects. However,the system characteristics involved are sufficiently broad that they may be used for policy analysis based on DYNAMO simulation results.

(1) BASIC MODEL BEHAVIOR

There are several key dynamic variables during the project life as shown on Fig.4. The project initiated at zero time with planned completion time of 30 months. Assuming a normal productivity of 2 units per man-month, the project effort is 600 man-month of R&D work. If we spread this effort evenly over 30 months, it will require 20 engineers/scientists on the project.

Under this initial condition, the average productivity of R&D person is less than 2 units. A basic problem in R&D is the relative intangibility for most of the work, particularly during the early phases of a research project. Because of the intangibility, in general the perceived (and scheduled) progress, based on 2 units per man-month, cumulates at a faster rate than the actual progress (shown as the "A" curve in Fig.4). And, this formed gap is not detected until month 18 in the simulation, from that date changes begin in project behavior. Two observable changes would occur.

First, under schedule pressure due to the deviation of fo-

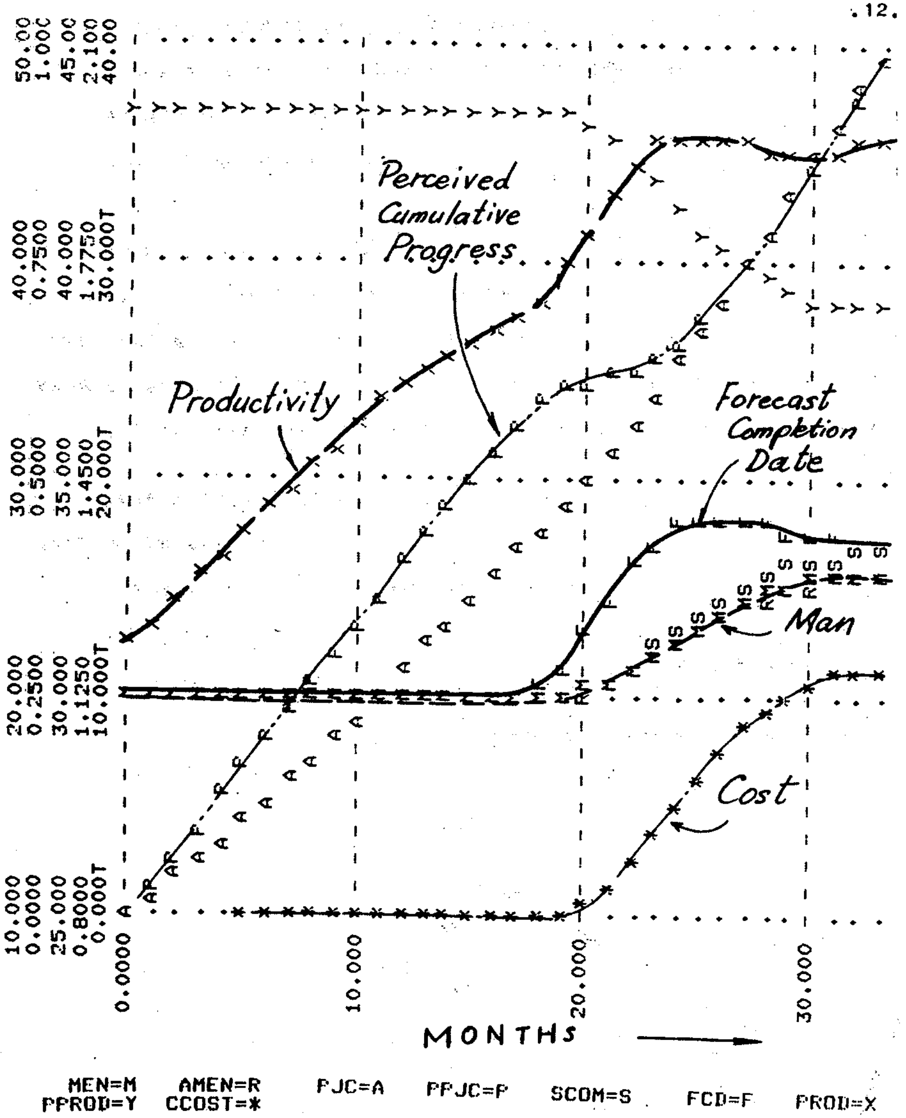


Fig.4 Basic Model Simulation

recast completion from schedule, productivity of R&D persons begin to rise, peaking at nearly 2(more than 1.9) job units per man-month,i.e, about an increase of 20% than the productivity of early period. This rising productivity gradually drops down as the gap between forecast and schedule getting smaller and smaller.

The second change is that the firm assigns more R&D work force to the project, going from initial level of 20 men up to 25 persons at nearly the end of the project completion date.

These changes result in project completion during month 33, 10 percent slippage of the original schedule. The total effort required is 709 man-months, in contrast to the ideal case of 600 man-months. Be sure that the increasing productivity starting about month 19 does give benefit to the completion of the project. This productivity change thus produces approximately 5 percent saving of total effort, hence, total cost in the project.

(2) PLANNING IMPROVEMENT---ACCURATE PROGRESS PERCEPTION

The serious problem discussed in the preceding section is that lack of tangibility results in delay until the 18th month in the recognition of project problems. If we take the policy of improving planning and the measure of accurate progress perception,i.e, any error in perceived progress is immediately detected and corrected. Under this policy, an experiment of project simulation is made and illustrated in Fig.5,

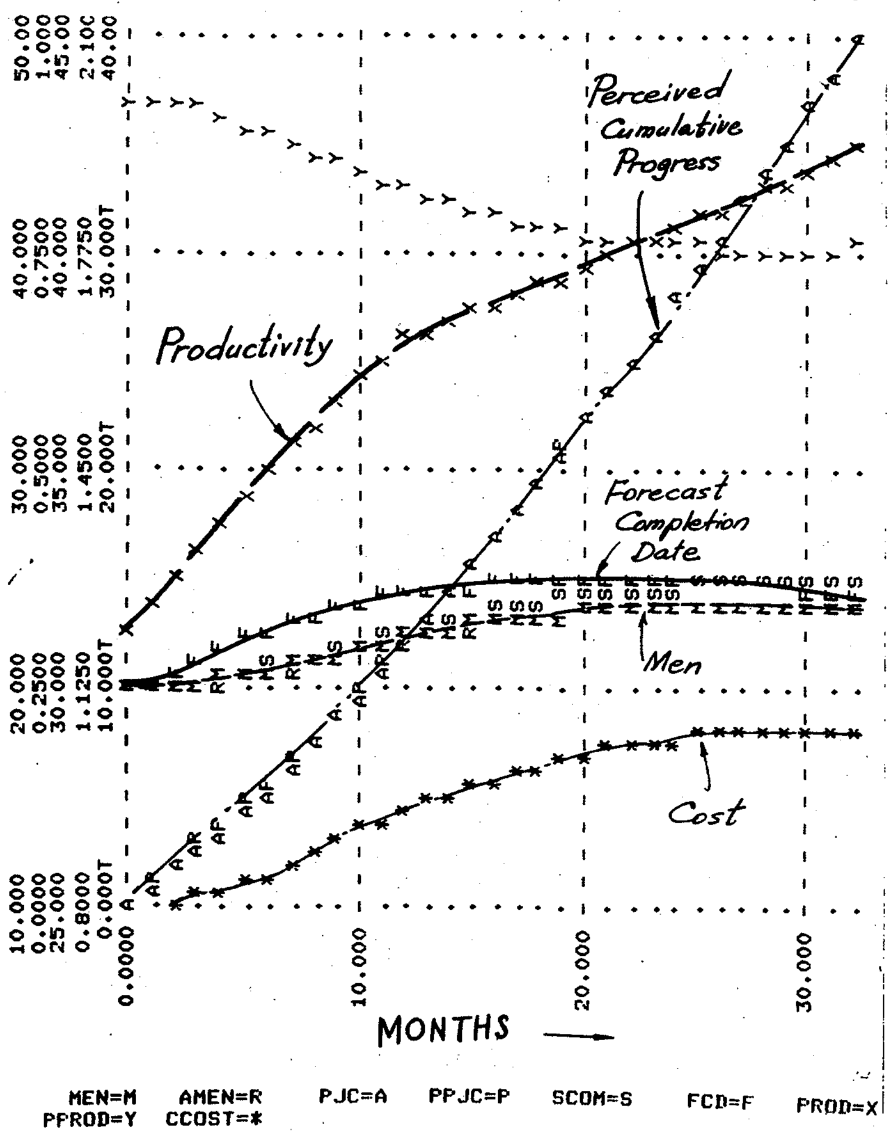


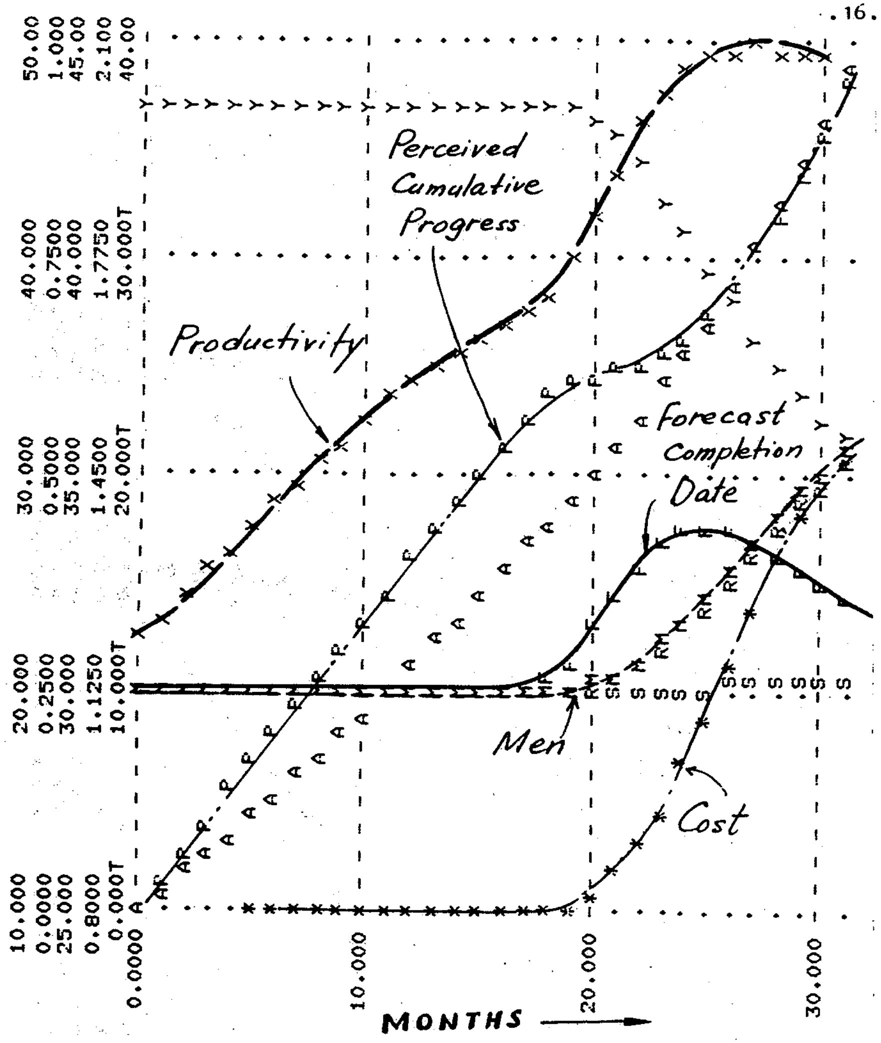
Fig.5 Plan Improvement: Accurate Progress Perception

here perceived actual progress remain together throughout the project. Cumulative required effort is 722 man-months, slightly more than those in the basic model simulation, but other benefits results from the accurate progress perception. The project is completed during month 32, 2 months behind initial schedule, but 1 month ahead of fore-mentioned basic case. Furthermore, peak manpower is 24 R&D persons instead of 26 of the basic case, which creates a certain extensive improvement in stability of the organization. These results, however, are not significantly different from the earlier basic case.

Policies for managing R&D projects give significant influence on the results. The next three policies are those related to schedule and R&D work-force changes.

(3) SCHEDULE-FIRST POLICY

According to this policy, the completion following to schedule is the first-of-all policy, in which the initially regulated schedule is treated as fixed rather than flexible. This policy is employed under the circumstances of urgent mission to be accomplished, of short-line or "bottle neck" subsystem within a complex project of large-scale system, as well as in the situation of "crash" project and many other R&D project in which the time of completion is given the highest priority. The simulation results under this policy shown in Fig.6 demonstrate that as the forecast completion date rises in response to recognition of errors in progress perception, the scheduled completion date is held nearly fixed at its initial regulated period.



MEN=M AMEN=R PJC=A PPJC=P SCOM=S FCD=F PROD=X
PPROD=Y CCOST=*

Fig.6 Schedule-First Policy

Several principal change results:

* The productivity rises significantly, peaking at more than 2 units per man-month during 27th month, an increase of near 40 percent over initial productivity.
* The manpower level on the project is greatly increased, rising up to more than 31 persons, i.e, an increase of more than 50 percent over the original level of 20.
* The cost level on the project is highly raised, increasing up to more than 35 percent over the basic case and the situation under other policies.
* The project is completed by the month 31, a slight delay of 1 month behind the original schedule.

(4) FIXED-MANPOWER POLICY

Under this policy no work-force change is made to respond to small change in schedule. This policy is usually used for basic research work at early period, or for no time limitation project. The result of simulation shown in Fig.7, indicate:

* Give no changes in the level of R&D work-force during the entire project period as well as no big changes in the cost level.
* Significant effects on productivity push this variable to a peak of 2 units per man-month during 25-26 months.
* Project is completed by the end of month 35, 5 month lag behind the original schedule.
* Total effort needed reaches the minimum level of 700 man-month, reflecting the rising of productivity.

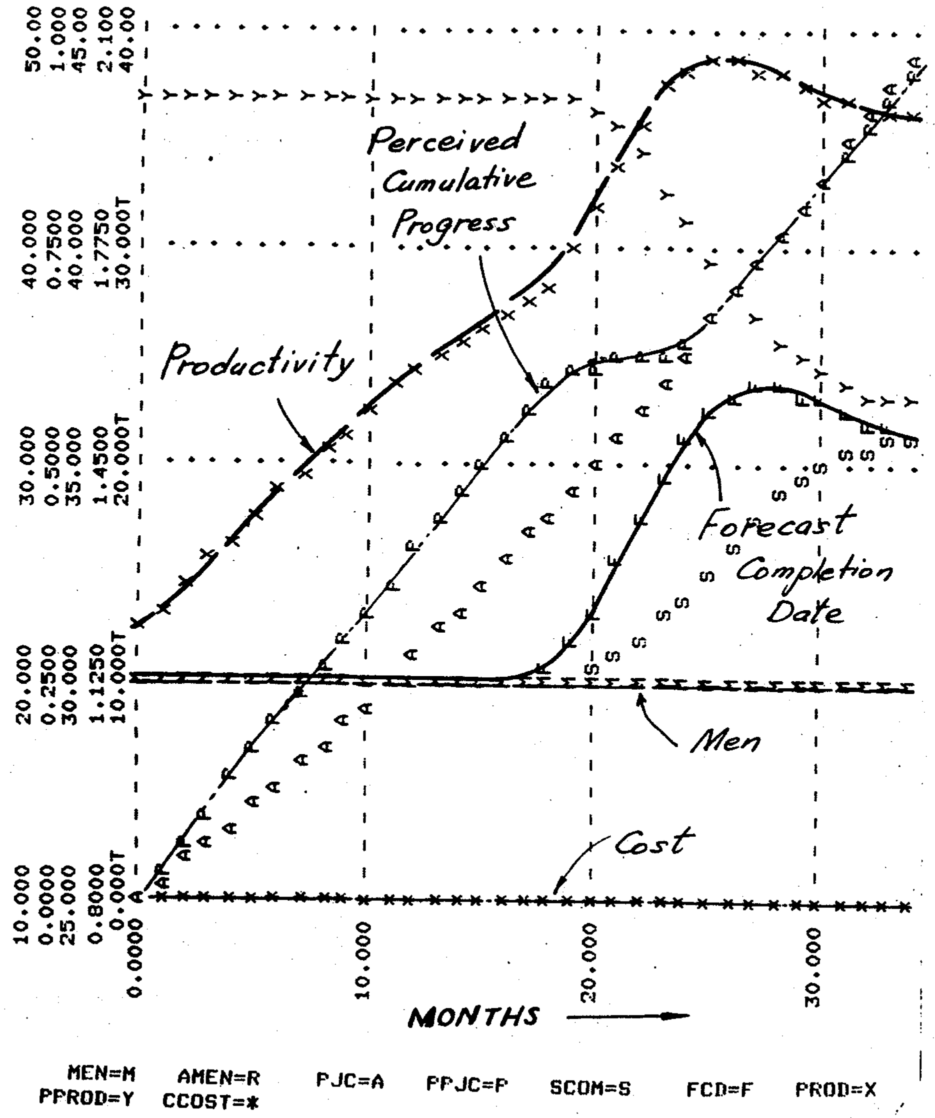


Fig.7 Fixed-manpower Policy

(5) IMMEDIATE SCHEDULE ADJUSTMENT POLICY

Under this policy, schedules are immediately adjusted to correspond with changed forecast of project completion time. This policy is much more similar to fixed-manpower policy through frequently and in-time adjustment of schedules. Such policy usually submits to limiting level of funding or limited pool of skillful R&D work-force with no strict limitation on project completion date, such as research project at earlier period. Alternatively, it may arise from the lack of the availability of additional R&D work-force to be assigned to the project. In any one of above cases, once detected problems result in a later forecast completion date, the schedule is adjusted to match the forecast. Under such a policy several characteristics can be found in the simulation results (see Fig.8):

* Due to no schedule pressure, there is no additional pressure or motivation to change the rate of production of the R&D work-forces.
* The organization size could be maintained at a stable level, raising less than one person during the whole project life.
* A delay completion date with a big slippage of 6 months, i.e, 20 percent over the original schedule.
* As the penalty to the low productivity gains during the project, with 726 man-month on the project (20 percent over the ideal case of 600 man-month) and the highest cost of 1.6 million yuan.

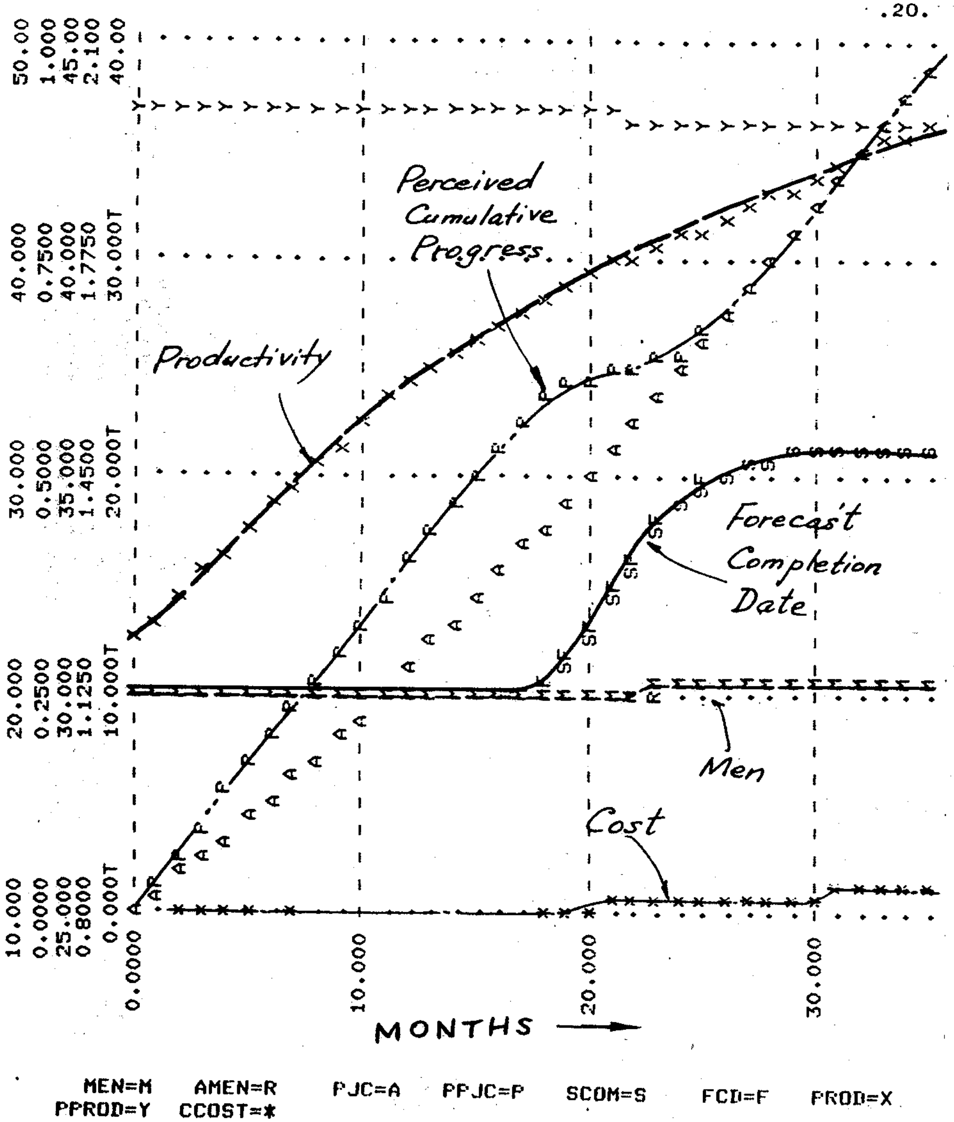


Fig.8 Intermediate Schedule Adjustment

BRIEF CONCLUTION

For the sake of policy choice, a table involving all the simulation results indices of various policies mentioned above is indicated in table 1.

Policy \ Index	Completion Date (month)	Cost (million yuan)	Peaking Workforce (men)	Efforts (man-month)
* Basic	33	1.56	26	709
* Accurate progress perception	32	1.59	24	722
* Schedule-first	31	2.02	31.5	713
* Fixed-manpower (min. cost)	35	1.54	20	700
* Immediate schedule adjust	36	1.60	20.5	726

* System Dynamics is an effective methodology, offering a lot dynamic simulation data for policy analysis. Concequently the policy will be selected according to the objectives and strategy conducted by the environment.

* Each policy has its own characteristics and strategic stress, as well as its advantages and shortcomings. The choice of policy must be submitted to the main goal, i.e, the objectives of the R&D plan. For instance, in our case, if the highest priority of planning is set on completion date, then the policies of accurate progress perception and schedule-first policy will be the best. Under the situation of limited workforce, fixed-manpower policy and immediate schedule adjustment

would be the best.

* Under particular major specified purpose a satisfactory policy in most or all dimensions can be searched though a great deal simulation by system dynamics modeling. In this case basic policy seems to be a satisfactory one in all dimensions.

* Concequently, system dynamics may serve as a multi-variable decision making approach in R&D project planning, as well as in the other cases.

Ref.

Edward B. Roberts, Managerial Applications of System Dynamics, 1978

APPENDIX

RESEARCH AND DEVELOPMENT PROJECT MODEL

```
          **********     PROGRESS      **********
L    PCP.K=PCP.J+(DT)(PPR.JK+PECR.JK)
N    PCP=0
R    PPR.KL=(MEN.K)(PPROD.K)
A    PPJC.K=PCP.K/ER
C    ER=1200
         PCP--PERCEIVED CUMULATIVE PROGRESS (JOB UNIT)
         PPR--PERCEIVED PROGRESS RATE (JOB UNIT/MONTH)
         PECR--PERCEIVED ERROR CORRECTION RATE (JOB UNIT/MONTH)
         MEN--MEN ON JOB
         PPROD--PERCEIVED PRODUCTIVITY ( JOB UNIT/MAN-MONTH )
         PPJC--PERCEIVED PERCENTAGE OF JOB COMPLETED ( % )
         ER--EFFORT REQUIRED ( JOB UNITS )

L    CRP.K=CRP.J+(DT)(PR.JK)
N    CRP=0
R    PR.KL=(AMEN.K)(PROD.K)
         CRP--CUMULATIVE REAL PROGRESS (JOB UNITS)
         PR--PROGRESS RATE (JOB UNIT / MONTH)
         AMEN--AVERAGE MEN ON PROJECT
R    PECR.KL=(FER.K)(CRP.K-PCP.K)
A    FER.K=TABLE(TFER,PJC.K,0,1,0.2)
T    TFER=0,0,0,.5,.8,1
A    PJC.K=CRP.K/ER
         PECR--PERCEIVED ERROR CORRECTION RATE (JOB UNIT/MONTH)
         FER--FRACTION OF ERROR RECOGNIZED ( % / MONTH )
         CRP--CUMULATIVE REAL PROGRESS
         TFER--TABLE, FRACTION OF ERROR RECOGNIZED ( % / MONTH )
         PJC--PERCENTAGE OF JOB COMPLETED ( % )

L    PPROD.K=PPROD.J+(DT)(CPPR.JK)
N    PPROD=PRODN
R    CPPR.KL=(FCPP.K)(PPROD.K)
A    FCPP.K=TABLE(TFCPP,RFSC.K,0,2,.2)
T    TFCPP=.25/.23/.2/.15/.08/0/-.05/-.07/-.11/-.21/-.4
         CPPR--CHANGE IN PERCEIVED PRODUCTIVITY ( JOB UNITES/
             MAN-MONTH/MONTH )
         PRODN--PRODUCTIVITY, NORMAL (JOB UNITS/ MAN-MONTH )
         FCPP--FRACTIONAL CHANGE IN PERCEIVED PRODUCYIVITY
               ( % / MONTH )
         TFCPP--TABLE, FRACTIONAL CHANGE IN PERCEIVED PRODUC-
               TIVITY ( % / MONTH )
```

```
    **********     PRODUCTIVITY     ***********

A      PROD.K=(PM.K)(PRODN)(NPF.K)
C      PRODN=2
A      PM.K=TABLE(TPM,RFSC.K,0,2,.25)
T      TPM=.6/.65/.75/.85/1/1.3/1.5/1.6/1.45/1/.8
A      NPF.K=TABLE(TNPF,TIME.K,0,72,6)
T      TNPF=.6/.7/.8/.85/.9/.95/1/1.02/1.04/1.055/1.065/1.075/1.082
              NPF--NORM PERFORMANCE FACTOR (SKILL FROM PRACTICE OVER
               TIME,DIMENSIONLESS)
              CLIP--CLIP FUNCTION
              PM--PRODUCTIVITY MULTIPLIER
              PRODN--PRODUCTIVITY , NORMAL (JOB UNIT/MAN-MONTH )
              TPM--TABLE PRODUCTIVITY MULTIPLIER

A      RFSC.K=FCD.K/SCOM.K
              RFSC--RATIO OF FORECAST TO SCHEDULED COMPLETION DATE
                    (DIMENSIONLESS)
              FCD--FORECAST COMPLETION DATE (MONTHS)
              SCOM--SCHEDULED COMPLETION DATE (MONTHS)

A      FCD.K=TIME.K+ITR.K
A      ITR.K=EBR.K/(PPROD.K*MEN.K)
A      EBR.K=ER-PCP.K
              ITR--INDICATED TIME REMAINING (MONTHS)
              EBR--EFFORT BELEIVED REMAINING (JOB UNITS)

L      SCOM.K=SCOM.J+(DT)(1/DCS)(FCD.J-SCOM.J)
N      SCOM=FCD
C      DCS=6
              DCS--DELAY IN CHANGING SCHEDULE (MONTHS)

    **********     MANPOWER     **********

L      MEN.K=MEN.J+(DT)(MENCH.JK)
N      MEN=ER/(DCOMI*PPROD)
C      DCOMI=30
              MEN--MEN ON PROJECT
              MENCH--MEN CHANGE RATE (MEN/MONTH)
              DCMOI--DESIRED COMPLETION DATE INITIALLY ( MONTHS )
              PPROD--PERCEIVED PRODUCTIVITY (JOB UNITS/MAN-MONTH)

R      MENCH.KL=FCHM.K*MEN.K
A      FCHM.K=TABLE(TFCHM,RFSC.K,0,2,.25)
T      TFCHM=-.65/-.4/-.2/-.1/0/.1/.2/.4/.65
              FCHM--FRACTION CHANGE IN MANPOWER
              TFCHM--TABLE, FRACTION CHANGE IN MANPOWER ( % / MONTH )

L      AMEN.K=AMEN.J+(DT)(1/DAMEN)(MEN.J-AMEN.J)
N      AMEN=MEN
C      DAMEN=1
              DAMEN--DELAY IN AVERAGING MEN ON PROJECT (MONTHS)
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```
    **********     CHANGE IN COST     **********

L      CMEN.K=CMEN.J+(DT)(MENCH.JK)
N      CMEN=0
A      CCOST.K=WEPMM*CMEN.K
C      WEPMM=1980  YUANS
              CMEN--CUMULATIVE MEN ON PROJECT (MAN-MONTH)
              CCOST--CUMULATIVE COST ( YUANS )
              WEPMM--WAGE PLUS EXPENSES PER MAN-MONTH (YUANS)

    **********     SIMULATION SPECIFICATION     **********

A      LENGTH.K=CLIP(0,50,PJC.K,1)

PLOT MEN=M,AMEN=R(10,50)/PJC=A,PPJC=P(0,1)/SCOM=S,FCD=F(25,45)
X1 /PROD=X,PPROD=Y(.8,2.1)/CCOST=*(0,4E4)
PRINT PJC,PPJC,SCOM,FCD,PROD,PPROD,CMEN,AMEN,CCOST
SPEC DT=.5/PLTPER=1/PRTPER=3
RUN CONCISE MODEL
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