An application of System Dynamics to the Construction Management of a Major Building

Jean-Claude Huot and Yves Sylvestre
Centre for Building Studies
Concordia University, Montreal Canada

ABSTRACT

In the past, the most popular computer models for the construction management of major buildings were large models based on the graph theory and their consequent discrete event simulation on the mainframe computer to have a view of the operational level. We think that in the future if we want to remain competitive on the world market the trend will be the use of small system dynamics generic models in relation to micro-computers at the strategic management level that can generate the reference modes i.e. the project control baselines.

INTRODUCTION

In the last thirty years, there has been a remarkable growth in number, size and complexity of MACRO-Engineering Projects, including Major Buildings. To handle the construction of these complex projects succesfully, powerful computer oriented techniques of control have been developed in the last twenty years.

These computer models, developed for management at the operational level, i.e. for project control at the bottom level, have revealed themselves to be inadequate at the top level for strategic management purposes.

In the past, for Major Projects, there have been no formal strategic approaches to help construction management executives to find the net effect of their policies on the project control baselines and consequently on the construction delays and cost overruns.

Now, the technology exists for Top Management to help evaluate the impact cost caused by a disruption of work due to the decisions of Owners since Pugh-Roberts Associates have developed for the mainframe computers: the Program Management Modelling System (P.M.M.S) that has been applied succesfully to resolve a $500 million claim against the U.S. Navy in late 1970's.

We are of the opinion that to develop a better sense of vision in the realization of large scale programs in general and major fast-track buildings in particular, we need to develop an appropriated educational set of small generic structures with the system dynamics methodology.

The object of this paper is to present our preliminary research on one such structure and to demonstrate its usefulness in the context of the analysis of different strategies to build a giant skyscraper.

THE NEED FOR EFFECTIVE STRATEGIC PLANNING TOOLS IN THE CONSTRUCTION OF MAJOR BUILDINGS

Before attempting the realization of any future giant skyscraper (in New York a building of 150 floors with a height of 1,940 feet is envisaged while in Chicago it is a building of 250 floors with a height of more than 2,000 feet), we think that it shall be prudent to establish a system dynamics model. At this moment we deplore the absence of any proper system approach to tackel the strategic management level of major projects.

To close this gap, the Center for Building Studies of Concordia University has given attention to system dynamics and initiated with the Natural Sciences and Engineering Research Council of Canada a small research program to investigate the usefulness of the methodology as to the construction management of buildings.

In the construction of major buildings we are convinced of the utility of system dynamics as a very helpful tool, not only for Top Management but also for arbitrators to assess impact costs caused by a production rate decrease due to disruption of work on account of change orders from the Owner, the designers, or the field.

WHY DO WE FAST-TRACK CONSTRUCTION OF LARGE SCALE PROJECTS?

For economical reasons on account of size, we cannot realize a large project with the traditional conventional construction method in one unique package following the rigid procedure of the design-procure-construct phases, the duration of the total project would be too long. It is more economic to fast-track large projects because we save up to 30% of the time on the normal schedule of a conventional project realized in rigid and independant phases. Fast-tracking can reduce from 30 to 50% the cost of a conventional undertaking on account of escalation on material and the cost of borrowed money. Long delays of certain material deliveries and borrowing money cost millions of dollars. This applies also to large scale buildings such as skyscrapers.

In a fast-track construction, we build at the same time that we design. A fast-track project is realized in design/built packages configurated to suit the needs of the constuction. But this is not a full proof process in terms of quality and productivity.

A fast-track project generates rip-out and rework, not only on the design table but also on the field. Rip-out and rework are equivalent to negative productivity and affect the morale of workers and the dynamics of program performance. Major buildings are highly sensitive to quality control and schedule pressure. Extended delivery time, reduction of material availability, and schedule pressure result in work out of sequence, jeopardizing the cash flow and consequently the internal rate of return of the project.

In a fast-track we subdivide the project in many work packages that are going to become more and more precise as the definition of the scope develops through configuration management. We plan the construction of the first packages as soon as possible and we try to maintain continuity and avoid disruption in the continuous design/built process. In this process, the designer and the contractor are working more closely and often the designer is part of the contractor organization, in what we call a Design/build company.

Reciprocal relationships exist between the designer and the contractor in each package. In a major fast-track project, it is almost impossible with traditional operational methodological approaches to establish claims on "delay and disruption' costs- and third -order "ripple effects of dealing with direct changes on original scope.

On account of reciprocal relationships in a fast-track project, we need a tool to properly assess the impact of scope changes on the project control baselines, such as duration, budget, quality and productivity. This can be achieved with system dynamics.

PROJECT CONTROL BASELINES VS BEHAVIOUR MODES

We can define any project by a certain number of parameters like time, cost, manhour resources, rate of productivity, etc. and those parameters can be associated with the design and construction behaviourial modes of the project to become the project control baselines. A baseline is a control pattern on a time scale.

Some of the control patterns we have identified in our model are:

- the duration of the project;
- the human resources to be used on the project;
- the productivity of the project;
- the total cost of the project;
- the time remaining to scheduled completion date;
- the perceived progress.

When those modes of behaviour dependent on specific policies have been established by the simulation process according to a specific strategy, they become the project control baselines of the project. Project control baselines are indicators that are necessary to evaluate performance deviation.

PRODUCTIVITY IS THE MOST IMPORTANT BEHAVIOUR MODE IN THE CONSTRUCTION OF MAJOR PROJECTS

Productivity is the most severe problem on large projects as identified in many studies in the 1970's, especially in the projects with a high degree of complexity and with a dimension of R & D. In our opinion, system dynamics models can help us to understand the productivity phenomenon in major projects by its original handling of both complexity and R & D.

In the model we are about to see, we have given equal attention to design productivity and construction productivity because differenciation between design and field labor is essential for better strategic planning and project control.

We have considered the effect of the learning curves of the different specialities and the trapezoidal distribution of the working resources on productivity. We believe that there is a relation between quality and productivity. A better productivity has a tendency to improve quality and most of the time poor productivity means poor quality. In a fast-track project, the degree of overlap on design-construction has an effect on productivity and consequently on quality.

DESCRIPTION OF THE MODEL

The model consists of the assembly of three subsystems: design and construction, which each represents an assembly of three important sectors (workforce, progress and scheduling) and the procurement subsystem for procurement progress. All of this has the following functions (see figure 1 and table 1.):

- the design subsystem describes how drawings are produced;

- the procurement subsystem simulates requisitions, purchase orders and delivery of material, starting from the design's evolution;

- the construction subsystem describes the physical progress of the project, taking into account the two previous subsystems.

In those subsystems, the management estimates the remaining work at each simulation step, and forecasts the global delay and the final delivery date. From these estimates, the management sector may shift the workforce betweem the different tasks, or may take people from the company's other projects. It may also be necessary on occasion to change the schedule and the final delivery date.

In this model, the user decides when procurement and construction processes start and can evaluate from different design-procurement-construction overlap schemes, the optimal solution that minimizes duration, cost and maximizes quality and productivity.

BASIC CAUSAL LOOPS FOR THE DESIGN AND CONSTRUCTION SUBSYSTEMS

The design and construction subsystems are each composed of three major loops: two negative loops and one positive loop (see figures 2 and 3).

The major negative loop has the goal to realize the project: as the workforce goes up, the progress rate and the cumulative progress go up, then the tasks perceived remaining go in the opposite direction; when the tasks remaining go down, the effort remaining, the indicated workforce, the net hiring and the total workforce go in the same direction.

The second negative loop works as follows: when it is recognized that the forecast schedule completion date is behind schedule, the schedule pressure increases, the workers and the management will increase the work rate to be on the target date, reducing the pressure on the schedule.

At the same time, the schedule pressure will decrease the quality of

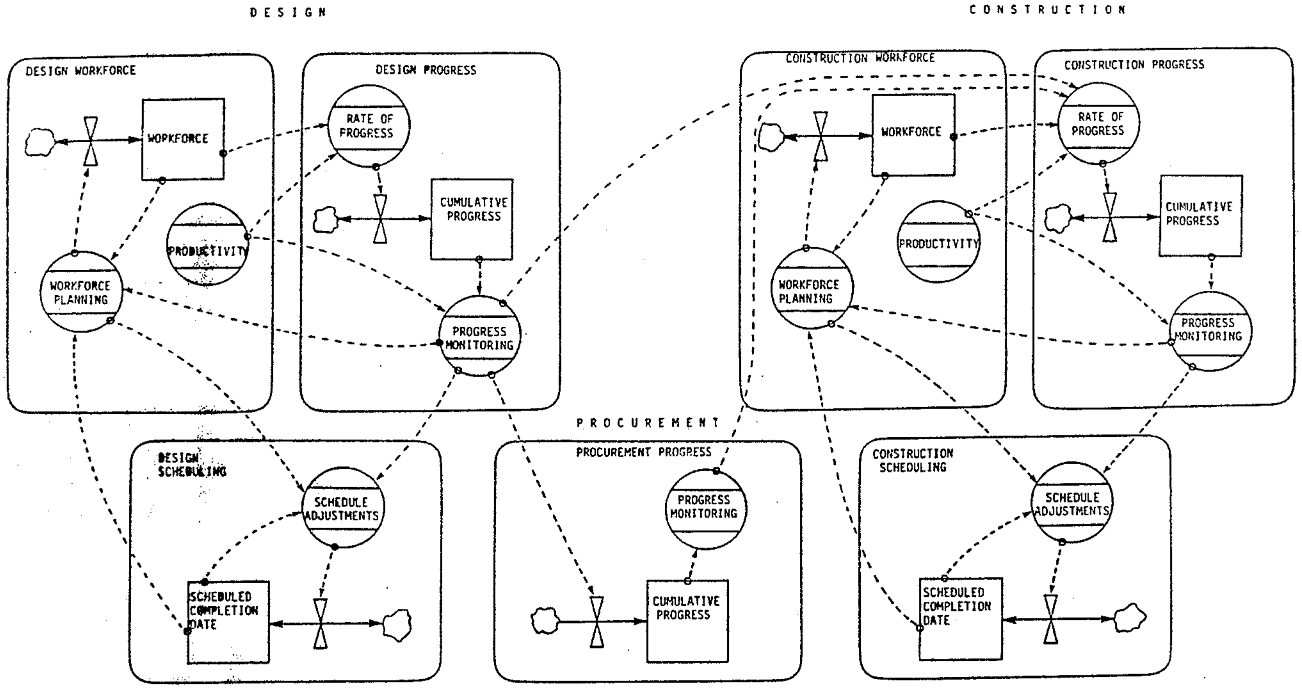

FIGURE 1 ; POLICY STRUCTURE DIAGRAM OF A LARGE BUILDING PROJECT MODEL

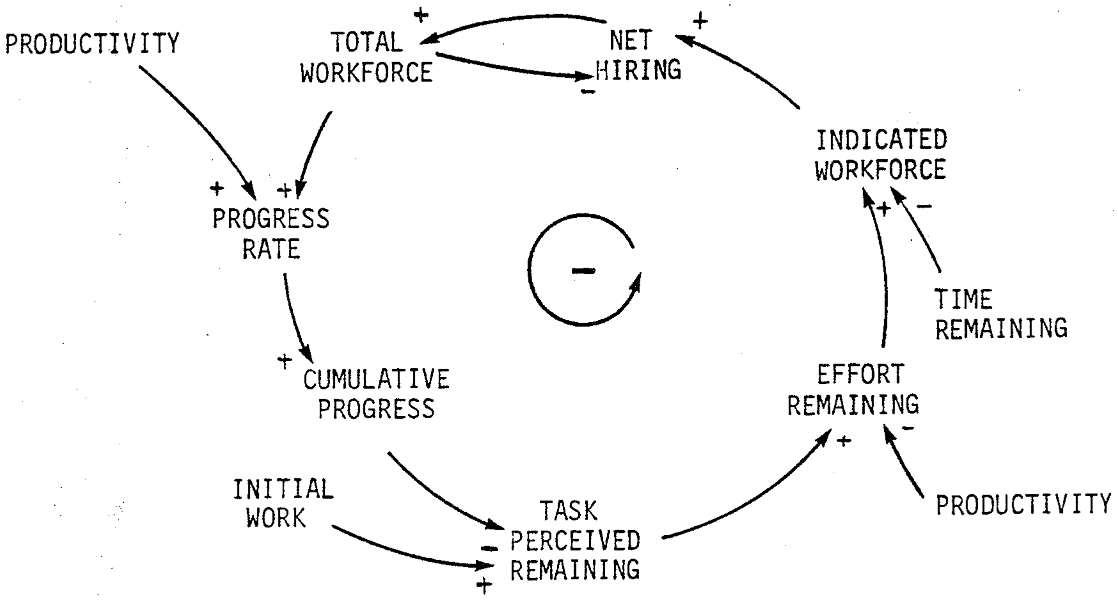

FIGURE 2

TABLE 1 : EQUATIONS OF THE LARGE BUILDING MODEL FOR PROCUREMENT AND CONSTRUCTION ONLY

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NOTE
NOTE
NOTE      CONSTRUCTION  CONSTRUCTION  CONSTRUCTION CONSTRUCTION
NOTE
NOTE      QUALITY OF CONST.
A QC.K=SMOOTH(TABHL(TQC,FPCONC.K,0,1,.1)*TABHL(TQNC,RRDCTD.K,
X 0,1,.2)*CWEQ.K*SCPEQC.K*EFDNQ.K,QDEL)
T TQNC=1,.99,.98,.96,.96,.96
T TQC=.99,.94,.98,.96,.93,.96,.98,.96,.94,.97,.95
NOTE      RATIO OF REVISED DRAWINGS TO TOTAL DRAWINGS
A RRDCTD.K=DTRASC.K/(TWA.K+IW)
NOTE      DRAWINGS TO REWORK AFTER THE  CONSTRUCTION START
L DTRASC.K=DTRASC.J+DT*RDRASC.J
N DTRASC=0
A CWEQ.K=TABHL(TWEQ,CWFQF.K,0,1,.2)
A CWFQF.K=CWFEXP.K/(TCWF.K+1)
A SCPEQC.K=TABHL(TSCPEQ,RRFSCC.K,0,3,.5)
NOTE
NOTE      CUMUL. PERCEIVED CONST.PROGRESS
NOTE
A CPCP.K=CNNR.K+UCNR.K
NOTE      FRACTION PERCEIVED COMPLETE OF CONSTRUCTION
A FPCONC.K=CPCP.K/TPCJ.K
NOTE
NOTE      CONST. EFFORT PERCEIVED REMAINING
A CEPREM.K=(TPCJ.K-CPCP.K)/CLIP(CPPROD.K,GPRODC,TIME.K,CONSST)
A TPCJ.K=(IW+TWA.K)*RCD
C RCD=6
A CPPROD.K=SMOOTH(IPRODC.K,TPPROD)
NOTE      INDICATED PRODUCTIVITY IN CONST.
A IPRODC.K=WTRPC.K*CRPROD.K+(1-WTRPC.K)*GPRODC
A CRPROD.K=CLIP(CNNR.K/((CCWFD.K+1)/5),CNNRP.K/((CWFEXP.K+CWFNEW.K+1)
X *DT),FPCONC.K,.99)
NOTE      PROCESS TO HAVE THE CONST. NOT NEEDING REWORK FOR EACH PERIOD
A RCNNR1.K=RCNNR.JK
L CNNRP.K=CNNRP.J+DT*(RCNNR1.J-RCNNR2.JK)
N CNNRP=0
R RCNNR2.KL=CNNRP.K/DT
A WTRPC.K=TABHL(TWTRP,FPCONC.K,0,1,.1)
NOTE
NOTE      SCHEDULING FOR THE CONSTRUCTION
NOTE
A TPREQC.K=CLIP(CEPREM.K*RTRAFC.K/MAX(CWFS.K,1),
X SCDC.K-CONSST,TIME.K,CONSST)
A RTRAFC.K=TABHL(TRTRFC,FPCONC.K,0,1,.1)
T TRTRFC=.15,.45,.71,.97,1.29,1.37,1.51,1.82,1.68,1.56,.01
A ICDC.K=SWITCH(CLIP(TIME.K+TPREQC.K,SCDD.K+SCDCN-SCDND,TIME.K,CONSST),
X CLIP(TIME.K+TPREQC.K,MAX(SCDD.K,SCDCN),TIME.K,CONSST),TEST1)
C TEST1=0
L SCDC.K=SCDC.J+DT*NACS.JK
N SCDC=SCDCN
C SCDCN=384
R NACS.KL=(ICDC.K-SCDC.K)/CSAT.K
A CSAT.K=TABHL(TSATC,FPCONC.K,0,1,.2)
T TSATC=20,20,10,6,4,3
A TREMC.K=CLIP(SCDC.K-TIME.K,SCDC.K-CONSST,TIME.K,CONSST)
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NOTE
NOTE      UNDISCOVERED CONST. NEEDING REWORK
NOTE
R RUCNR.KL=APPRGC.K*(1-QC.K)
L UCNR.K=UCNR.J+DT*(RUCNR.JK-RDUCNR.JK)
N UCNR=0
R RDUCNR.KL=UCNR.K/TDCRW.K
A TDCRW.K=TABHL(TTDRW,FPCONC.K,0,1,.1)
NOTE
NOTE      CONST. NOT NEEDING REWORK
NOTE
L CNNR.K=CNNR.J+DT*(RCNNR.JK-RCTRRD.JK)
N CNNR=0
R RCNNR.KL=APPRGC.K*QC.K
NOTE      CONSTRUCTION TO REWORK DUE TO REVISED DESIGN
R RCTRRD.KL=CLIP(RDRASC.K*RCD/TDCR,0,CNNR.K-(DTRASC.K*RCD/TDCR),0)
NOTE      DRAWING TO REWORK AFTER THE CONSTRUCTION IS STARTED
A RDRASC.K=(RDUDWR.JK+DTRDC.JK+DTRWA.JK)*CLIP(1,0,TIME.K,CONSST)
C TDCR=4
A APPRGC.K=TCWF.K*APRODC.K
NOTE
NOTE      APPARENT PRODUCTIVITYIN CONST.
NOTE
C GPRODC=.208
A SCPEPC.K=TABHL(TSPEP,RRFSCC.K,0,2,.25)
A APRODC.K=SCPEPC.K*GPRODC*LEPROC.K*EFDMP.K*EFAWLC.K*EFJSC.K*EFOVTC.K
NOTE      LEARNING EFFECT IN CONST.
A LEPROC.K=TABHL(TLEPC,FPCIWC.K,0,1,.1)-PULSE(L1,L2,L3)
T TLEPC=.95,1.04,.9,.90,.95,1.10,1.05,1,1.03,.96,.9
NOTE      EFFECT OF AREA WORKLOAD IN CONST.
A EFAWLC.K=TABHL(TEFAWL,RATCWF.K,80,160,20)
T TEFAWL=.85,.9,.95,.98,1
A RATCWF.K=CLIP(200,CLIP(FLAREA*NBRFLR.K/6,2*FLAREA,FPCONC.K,.25)
X /(TCWF.K+1),1-FPCONC.K,1)
C FLAREA=27000
A NBRFLR.K=(IW+TWA.K)*RCD*40*20/(.33*85*GPRODC*FLAREA)
NOTE      EFFECT OF OVERTIME IN CONST.
A EFOVTC.K=TABLE(TEFOVT,RONHWC.K,0,.8,.2)*((NHWC+OVRTHC.K)/NHWC)
T TEFOVT=1,.9,.83,.75,.68
A OVRTHC.K=TABHL(TOVRTC,RRFSCC.K,0,2,.5)*TESTOV
T TOVRTC=0,0,0,0,20
A RONHWC.K=OVRTHC.K/NHWC
C NHWC=40,TESTOV=0
NOTE      EFFECT OF JOB SIZE IN CPNST.
A EFJSC.K=TABHL(TEFJSC,TPCND.K*NHWC/5,0,6000000,1000000)
T TEFJSC=1.06,1,.98,.97,.96,.95,.92
NOTE      EFFECT OF HOLYDAYS (TWICE PER YEAR) ON LEARNING EFFECT
C L1=0.05,L2=24,L3=24
A FPCIWC.K=MIN(1,CPCP.K/(IW*RCD))
NOTE
NOTE      RECOGNISED RATIO OF FORECAST TO SCHEDULE COMPLETION DATE
NOTE
L RRFSCC.K=RRFSCC.J+DT*((RFSCC.J-RRFSCC.J)/DRSS)
N RRFSCC=RFSCC
A RFSCC.K=ICDC.K/SCDC.K
NOTE
NOTE      HIRING PROCESS IN CONST.
NOTE
A CWFND.K=(WCCWF.K*ICWF.K)+((1-WCCWF.K)*TCWF.K)
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A WCCWF.K=TABHL(TWCCWF,FPCOMC.K,0,1,.2)
T TWCCWF=1,1,1,1,1,1
A CWFS.K=MIN(CLTCWF.K,CWFND.K)
A CLTCWF.K=TABHL(TCTCWF,FPCOMC.K,0,1,.2)
T TCTCWF=6000,6000,6000,6000,6000,6000
A CWFGAP.K=CWFS.K-TCWF.K
R CHIRERT.KL=MAX(0,CWFGAP.K/CHIRDY)
C CHIRDY=2
A TCWF.K=(CWFEXP.K+CWFNEW.K)*CLIP(1,0,TIME.K,CONSST)
L CWFNEW.K=CWFNEW.J+DT*(CHIRERT.JK-ASINRC.JK-NEWCTR.J+TRTNCW.JK)
N CWFNEW=0
R ASINRC.KL=CWFNEW.K/ASIDYC
C ASIDYC=4
L CCWFD.K=CCWFD.J+DT*(TCWF.J*5*((NHWC+OVRTHC.J)/NHWC)*(1/DT))
N CCWFD=0
A NEWCTR.K=MIN(TRNFRC.K,CWFNEW.K/DT)
A TRNFRC.K=MAX(0,-CWFGAP.K/TRNSDY)
L CWFEXP.K=CWFEXP.J+DT*(ASINRC.JK-EXPTRC.J-QUITRC.JK-TRTNCW.JK)
R QUITRC.KL=CWFEXP.K/AVEPTC
C AVEPTC=60
A EXPTRC.K=MIN(CWFEXP.K/DT,TRNFRC.K-NEWCTR.K)
N CWFEXP=0
NOTE      INDICATEB CONST. WORKFORCE
A ICWF.K=(CEPREM.K/(TREMC.K+1))*RTRAFC.K*CLIP(1,0,TIME.K,CONSST)
A TPCMD.K=(CEPREM.K*5)+CCWFD.K
NOTE      COST
A TCCOST.K=TPCMD.K*8*20/.33
A TPCOST.K=(TDCOST.K+TCCOST.K)/2
A TCCOSC.K=CCWFD.K*8*20
A TDCCOS.K=TCCOSC.K+TCCOSD.K
NOTE
NOTE      SWITCH OF CONST. WORKFORCE (TWICE)
R TRTNCW.KL=(CWFEXP.K*.8/DT)*CLIP(1,0,SWTCHF.K*DT,1)
A SWTCHF.K=SWTCHR.JK
R SWTCHR.KL=(FSWTCH.K+SSWTCH.K)/DT
A FSWTCH.K=CLIP(1,0,FPCOMC.K,.22)*CLIP(0,1,SWTCH.K,1)
A SSWTCH.K=CLIP(1,0,FPCOMC.K,.60)*CLIP(0,1,SWTCH.K,2)
L SWTCH.K=SWTCH.J+DT*SWTCHR.JK
N SWTCH=0
NOTE
NOTE      MATERIAL ORDERS
NOTE
NOTE      POTENTIAL ORDERS OF MATERIAL IN RELATION WITH DESIGN PROGRESS
A PRMTL.K=TABHL(TPRMTL,FPCOMD.K,0,1,.2)
T TPRMTL=0,0,.05,.25,.50,1
NOTE      REQUISITIONS OF MATERIAL
L REQMTL.K=REQMTL.J+DT*(REQRML.JK-ODRMTL.JK)
N REQMTL=0
R REQRML.KL=((PRMTL.K-REQMTL.K-MTLODR.K-MTLOST.K)/REQDY)*
X CLIP(1,0,TIME.K,PROCST)
C REQDY=6
NOTE      ORDERS DELAY
C ORDY=4
NOTE      ORDERS RATE OF MATERIAL
R ODRMTL.KL=REQMTL.K/ORDY
NOTE      MATERIAL ORDERS
L MTLODR.K=MTLODR.J+DT*(ODRMTL.JK-DELRML.JK)
N MTLODR=0
NOTE      MATERIAL ON SITE
L MTLOST.K=MTLOST.J+DT*DELRML.JK
N MTLOST=0
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NOTE      DELIVERY RATE OF MATERIAL
R DELRML.KL=MTLODR.K/DELDY.K
NOTE      DELIVERY DELAY
A DELDY.K=TABHL(TDELDY,QDSD.K,0,1,.2)
T TDELDY=20,20,20,16,14,8
NOTE      QUALITY OF DESIGN OF SHOP DRAWINGS
A QDSD.K=TABHL(TQDSD,AVQD.K,.5,1,.1)
T TQDSD=.5,.6,.7,.8,.9,1
NOTE      SUMMATION OF QUALITY DESIGN
L SQD.K=SQD.J+DT*QDGN.J
N SQD=QD
NOTE      QUALITY OF DESIGN TO DETERMINE THE QUALITY OF SHOP DRAWINGS
A QDGN.K=CLIP(0,QD.K/DT,RFCOMD.K,1)
NOTE      AVERAGE QUALITY OF DESIGN
A AVQD.K=SQD.K/CLIP(SCDD.K,TIME.K+1,FPCOMD.K,1)
NOTE      EFFECT OF DELIVERED MATERIAL ON QUALITY OF CONSTRUCTION
A EFDMQ.K=TABHL(TEFDMQ,RMNTMD.K,.7,1,.1)
T TEFDMQ=.85,.92,.97,1
NOTE      RATIO OF MATL. ON SITE TO MATL. NEEDED
A RMNTMD.K=MTLOST.K/MAX(MTLND.K,.001)
NOTE      EFFECT OF DELIVERED MATERIAL ON PRODUCTIVITY (APPARENT)
A EFDMP.K=TABHL(TEFDMP,RMNTMD.K,0,1,.2)
T TEFDMP=0,.58,.70,.83,.93,1
NOTE      MATERIAL NEEDED (IN THEORY)
A MTLND.K=MIN(1,FPCOMC.K*DELYF)
C DELYF=1.1
NOTE
NOTE      CONTROL CARDS
NOTE
C CONSST=144,PROCST=120
C WA=0,T2=100,T3=999
C DC=0,T4=20,T5=30
SPEC DT=1/MAXLEN=500,PLTPER=8/SAVPER=8
A PRTPER.K=LENGTH.K
A LENGTH.K=CLIP(TIME.K,MAXLEN,RFCOMC.K,.99)
NOTE      REAL FRACTION COMPLETE OF CONST.
A RFCOMC.K=CNMR.K/((IW+TWA.K)*RCD)
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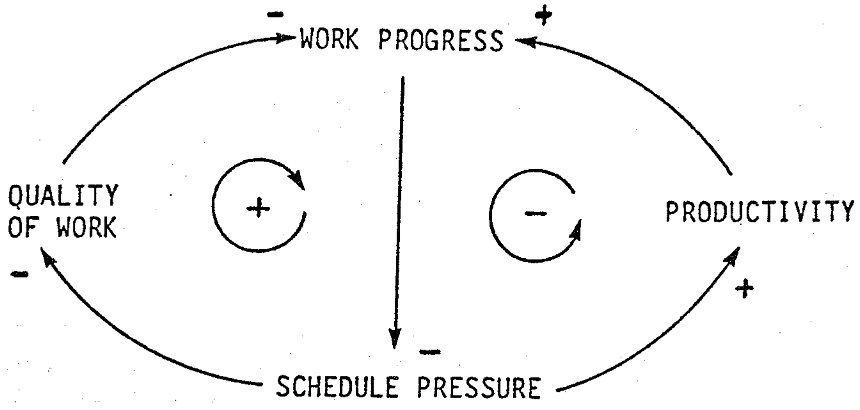


FIGURE 3

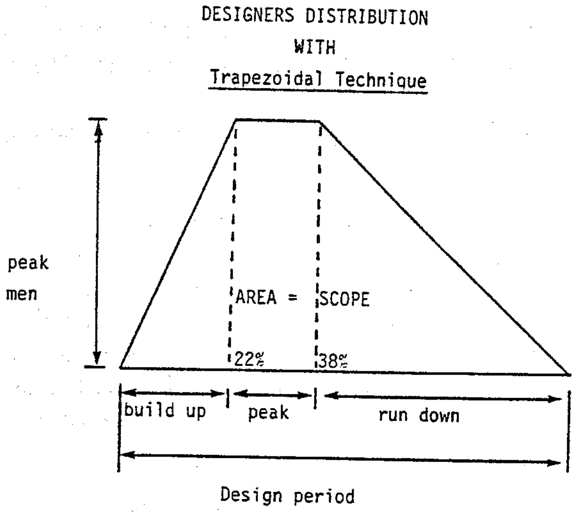


FIGURE 4

construction and then will reduce the rate of construction not needing rework and therefore maintains the slippage of construction schedule and the schedule pressure on workers; this is the positive loop.

THE DESIGN SUBSYSTEM

A mandate for the design/built of a skyscraper is undertaken by a Developer who hires Consulting-Engineers. A construction work breadown structure for fast-tracking the building is established according to scope configuration management and constructibility, which means that after preliminary engineering, the building project is packaged to be designed the way it is going to be built.

Preliminary engineering defines (besides the type and position of shearing walls, elevator lifts, curtain walls, beams, etc.,) the non similarities, like the different types of floors, typical cross sections, etc.; the final design consists of finalizing the details of each similarities. In buildings, there are sixteen specialities and to those specialities, a construction trade is corresponding. When you design/built, you will detail the structural design for about three floors ahead before you start the construction. In this process the design, procurement and construction are proceeding in sequential packages. We will assume an equal number of drawings for each floor. In this paper, the building has 250 floors.

After the approval of a preliminary architectural sketch, the architect will detail his drawings sufficiently to allow the structural engineer to design the building for the fondation and the infrastructure. At the same time, the electrical engineer and the mechanical engineer progress in the design in coordination with one another and with the interior designer.

The Consulting-Engineer starts with a certain number of designers in each specialities, but he will be obliged during the design process to hire designers in each speciality. The hiring is represented by the Hire Rate (HIRERD) and this is cumulated in a level, the Workforce NEW in Design (WFNEWD). After an assimilation period, this workforce becomes experienced (WFEXPD). The total distribution of resources is done trapezoidally during the design life cycle as required in practice. We asssume a complete build-up of the resources at 22% schedule progress and a run-down of the resources at 38% schedule progress (see figure 4):

The design effort perceived remaining (DEPREM) divided by the time remaining in design (TREMD) and multiplied by the required trapezoidal factor that varies with the progress of design, will determine the indicated workforce in design (IWFD).

The trapezoidal factor takes in account two parameters:

1- the required number of men using the trapezoidal distribution compared to the constant number of men using the rectangular distribution;

2- the effort perceived remaining using the trapezoidal distribution compared to the effort perceived remaining using the rectangular distribution.

The factors vary with the fraction perceived complete of design (FPCOMD) and are determined by the following table:

T TRTFD=.29,.78,1.32,1.45,1.52,1.47,1.42,1.37,1.24,1.11,.48

Different factors will be used for the construction workforce distribution.

The Design Workforce Sought (DWFS) will be measured also in regard of the Indicated Workforce (IWFD) and by the Ceiling to Design Workforce (CELDWF). If there are too many resources, the firing process or the Transfering Rate For Design (TRNFRD) will start by the new workforce (WFNEWD). The New Workforce (WFNEWD) with the Experienced Workforce (WFEXPD) represent the Total Design Workforce (TDWF) that will realize the design according to the Apparent PRODuctivity (APRODD) defined in function of a Gross PRODuctivity (GPRODD) that can be modified by the following three factors:

1- the SChedule Pressure Effect on Productivity in Design (SCPEPD);

2- the Learning Effect on PRODuctivity (LEPROD);

3- the EFfect of Job Size on Design (EFJSD).

The willingness to meet the target dates, especially when a project is late, has the consequence to increase the Schedule Pressure (SCPEPD) that will augment the productivity unless it is recognized impossible to meet the target date.

LEPROD implicates that the work becomes repetitive. The learning effect augments the apparent productivity (APRODD) up to the resource run-down of each discipline when there is no more production possible due to a lack of similar work.

EFJSD will decrease the productivity in a large project on account of the number of designers to coordinate and a slow down in the decision process.

PRODUCTION OF DRAWINGS

Our model considers the production of two types of drawings:

1- Drawings Not Needing Rework (DNNR);

2- Undiscovered Drawings Needing Rework (UDNR);

In practice, those drawings are function of the quality of design (QD) which will decrease slightly after the beginning, then will augment due to an increase of motivation for more construction quality and it will decrease at the end of the design of the corresponding speciality.

Anyhow, the quality of design (QD) will be affected by the experience of workforce (WEQD), by the schedule pressure effect on quality (SCPEQD) to meet the target date, by the effect of work added during the design (EWAQD) that has an effect of demotivation on the designers to produce quality work.

The drawings that do not need rework (DNNR) represent the cumulative real progress and are affected by design changes (DTRDC) that are requested by the owner, the consultants, a governmental department or the contractor and also by the work added (DTRWAD).

The time perceived required for the design (TPREQD) which determines the indicated completion date of design (ICDD), depends on the effort perceived remaining (DEPREM), the workforce sought (DWFS) and the trapezoidal factor.

In regard with the time perceived required, the management can modify the schedule completion date of design (SCDD) and adjust the indicated workforce for the design (IWFD) to meet the revised schedule date.

Design and construction subsystems have specific modules to differenciate design from construction for workforce, schedule completion date and apparent productivity.

THE CONSTRUCTION SUBSYSTEM (see figure 5)

In a fast-track project, the construction starts when there is enough material on site, between 30 and 40% of the total project time.

The general contractor plans his workforce sought (CWFS) in function of the schedule completion date (SCDC) stipulated in the tender document. To achieve this, we have distributed trapezoidaly the construction manpower with a build-up at 40% construction progress and a run-down starting at 70% construction progress:

The trapezoidal distribution of workers is composed of the sum of three major specialities: structural, mechanical-electrical and architectural, that are phasing at different times during the construction.

The experienced construction workforce (CWEXP) and the new construction workforce (CWFNEW) represent the total construction workforce (TCWF) that will carry on the construction according to an apparent productivity (APPRODC). Also the model transfers 80% of the experienced workers to new workers twice without hiring process.

The productivity will generally decrease when the following factors appears in the construction: fatique, decrease motivation, lack of work space, lack of effective direction, wrong number of skill types of workers, lack of proper material or equipment.

The Apparent Productivity in Construction (APRODC) is defined by this dynamo equation composed of a constant and six endogenous variables:

```
A APRODC.K=GPRODC*SCPEPC.K*LEPROC.K*EFDMP.K*EFAWLC.K*EFJSC.K*EFOVTC.K
```

where

GPRODC : Gross PRODuctivity (tasks/worker-week)

SCPEPC : SChedule Pressure Effect on Productivity (dimensionless)

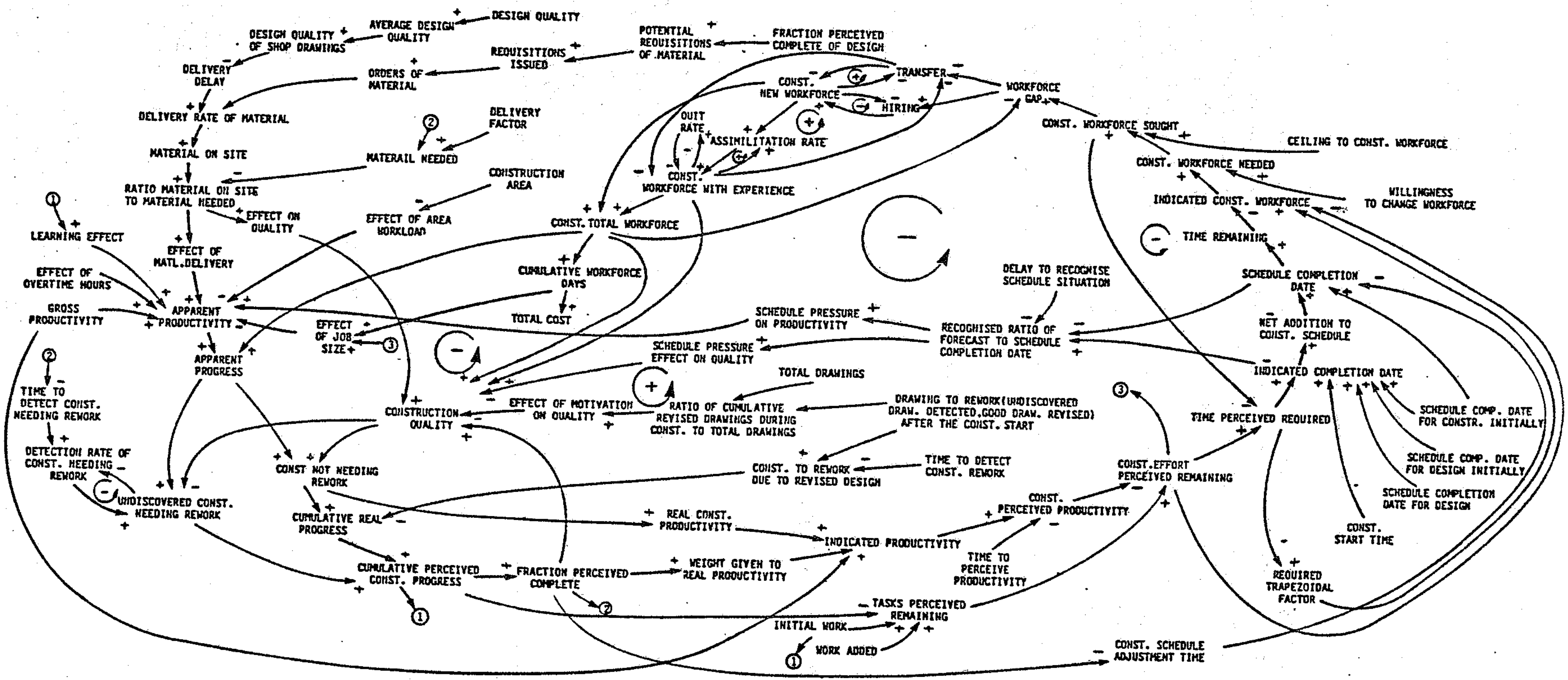


FIGURE 5 : CAUSAL LOOP DIAGRAM OF A CONSTRUCTION BUILDING PROJECT

LEPROC : Learning Effect on PROductivity (dimensionless)

EFDMP : EFfect of Delivery of Material on Productivity (dimensionless)

EFAWLC : EFfect of Area Workload (dimensionless)

EFOVTC : EFfect of OVerTime (dimensionless)

The gross productivity in construction is a constant; we assume a gross budgeted physical output for each man per unit of time. Because our concept of productivity in design is the rate at which drawings are produced, a physical measure without qualitative implications results to be 10 drawings/man/year; and it is also recognised that the construction manhour budget is about six times greater than in design. So we have considered this result and set the same value for the Gross PRODuctivity in Design (GPRODD) and in Construction (GPRODC) and assume every drawing generates six jobs in the field.

Those parameters involved in the Apparent Productivity are described hereafter:

1- the SChedule Pressure Effect on Productivity (SCPEPC):

SCPEPC varies in function of the recognized ratio of forecast to schedule completion date (RRFSCC).

A SCPEPC.K=TABHL(TSPEP,RRFSCC.K,0,2,.25)

T TSPEP=0.4,0.5,0.6,0.8,0.9,1,1.2,.9,.6

If the forecast completion date is ahead the schedule completion date the schedule pressure will have a negative effect on the construction productivity because the workers will tend to decrease the productivity to stay on the known target date. If the forecast completion date is behind the schedule completion date, the schedule pressure will have a positive effect on the productivity because the workers will try to stay on target date, unless the workers perceive that there is no possibility to be on the target date; in the last case, the productivity will decrease due to team demoralization (see figure 9).

2- the Learning Effect on PROductivity (LEPROC):

We have considered in our model the learning curve phenomenon on productivity. The construction of a skyscraper, on account of the similarities such as the typical floors, gives us the opportunity to study the learning effect on the productivity.

In the construction of a building, the learning curve is modified constantly because there are different learning curves due to the various specialities involved. Repetition of complex operations tends to exhibit high ratio of productivity improvement.

The Learning Effect on PRODuctivity in Construction (LEPRODC) is defined by a table, (TLEPC) that is the sum of the different learning curves (see figure 6). A pulse function takes into account the lost productivity on the learning

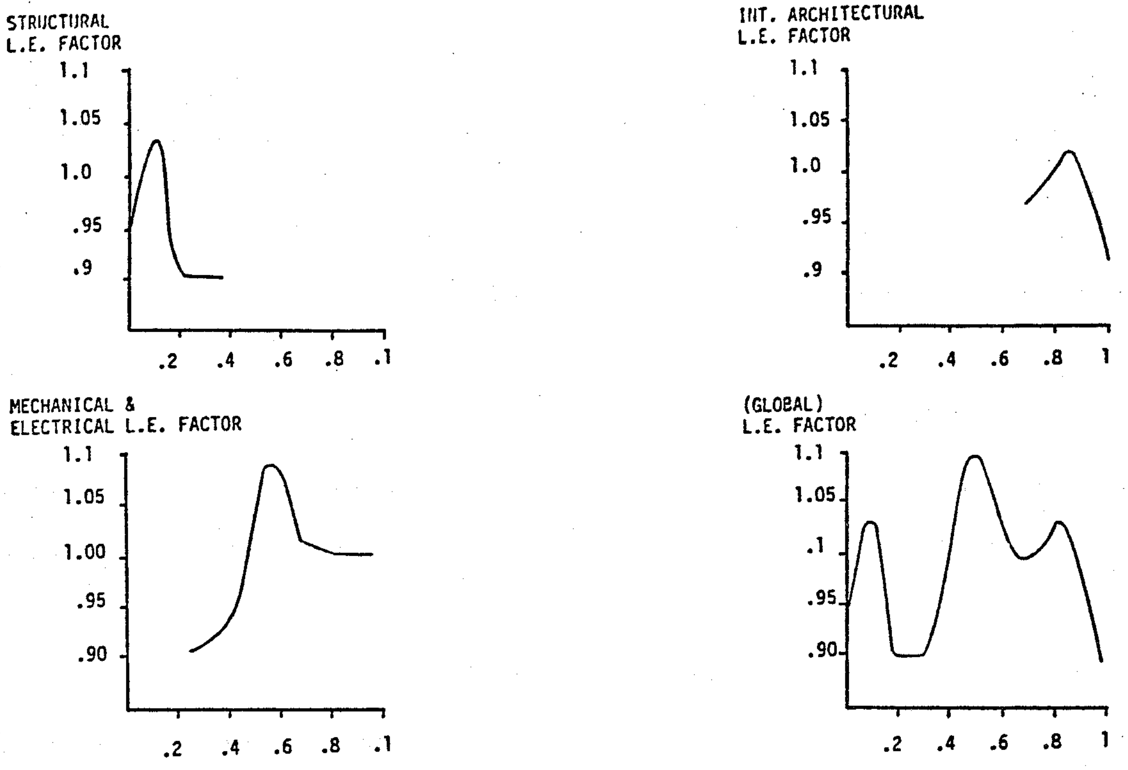


FIGURE 6 : LEARNING EFFECT ON CONSTRUCTION PRODUCTIVITY

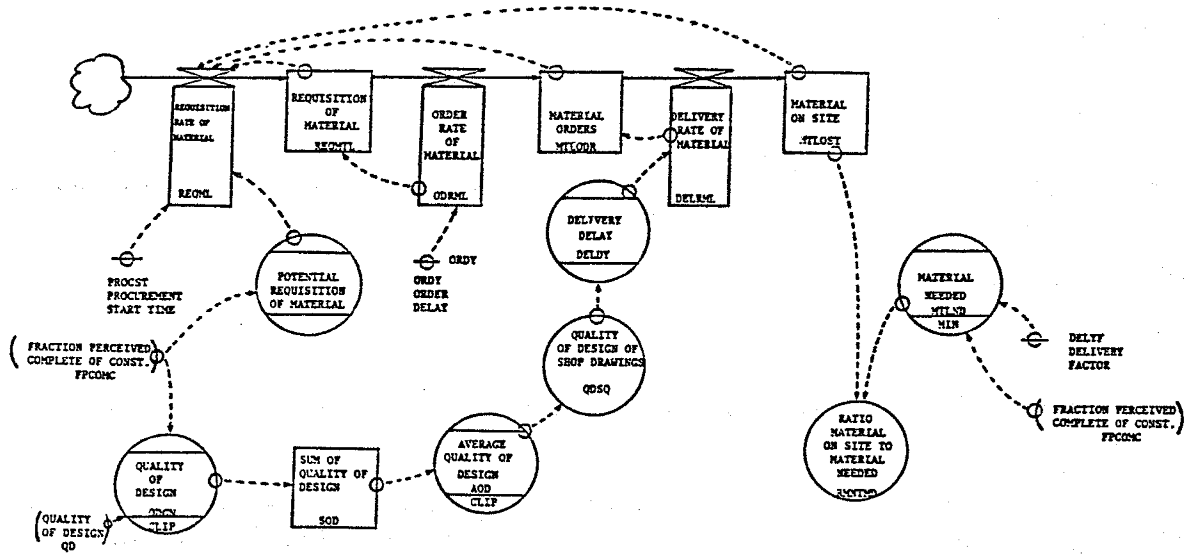


FIGURE 7 : PROCUREMENT SUBSYSTEM

curve due to the work interruptions, such as vacations. It is amazing to observe that the structural learning factor shows a rapid decrease of learning effect instead of an improvement.

```
A LEPRODC.K=TABHL(TLEPC,FPCIWC.K,0,1,.1)-PULSE(L1,L2,L3)
```

```
T TLEPC=.95,1.04,.90,.90,.95,1.1,1.05,1,1.03,.96,.9
```

Where L1, L2 and L3 equal respectively 0.05, 24 and 24.

```
A FPCIWC.K=MIN(1,CPCP.K/((IW)(RCD))
```

The learning effect factor must be in relation with the Fraction Perceive Complete of Initial Work in Construction (FPCIWC) which is the Cumulative Perceived Construction Progress divided by the Initial Work. The minimum function is used because the work done can be greater than the initial work if work is added.

3- the EFfect of Job Size in Construction (EFJSC):

The job size has a significant effect on productivity. By experience, we assume that the productivity decreases when the project construction manhours are over one million and increases under one million manhours:

```
A EFJSC.K=TABHL(TEFJSC,TPCMD.K*NHWC/5,0,6000000,1000000)
```

```
T TEFJSC=1.06,1,.98,.97,.96,.95,.92
```

TPCMD:Total Perceived Const. Man-Days.

NHWC:Normal Hours per Week in Construction.

4- the EFfect of Area WorkLoad in Construction (EFAWLC):

In construction, if there are too many workers in a work area, the productivity will be affected. We assume that the productivity will decrease if the area per man is under 160 feet:

```
A EFAWLC.K=TABHL(TEFAWL,RATCWF.K,80,160,20)
```

```
T TEFAWL=0.85,0.90,0.95,0.98,1
```

```
A RATCWF.K=CLIP(200,CLIP((FLAREA)(NBRFLR.K)/6,2(FLAREA),FPCOMC.K,0.25)
X  /(TCWF.K+1),1-FPCOMC.K,1)
```

The ratio of area to construction workforce (RATCWF) is defined by an assumed area divided by the total construction workforce (TCWF). The area of two floors is available to the circulation of the structural workers (progress less or equal to 25%) and 1/6 of the total floor area of the building is available to the circulation of the other specialities (progress greater than 25%).

C FLAREA=27,000 square feet, i.e. the area of one floor of the building.

```
A NBRFLR.K=(IW+TWA.K)*RCD*5*8*20/(.33*85*GPRODC*FLAREA)
```

A variable computes the number of floor (NBRFLR) of the building taking into account the initial work (IW) and total work added (TWA) converted in construction jobs (RCD), the cost per worker per week (5 day*8 hours/day*$22/hour), the expected percentage of the workforce cost in the total project cost (33%), the average construction cost per square feet ($85), the gross productivity (GPRODC) and the area of one floor (FLAREA).

5- the effect of delivery of material on productivity (EFDMP):

A lack of material affects the progress of work, the effect of delivery of material on productivity (EFDMP) is a table that varies between zero and one according to the Ratio of Material oN Site to Material neeDed (RMNTMD):

```
A EFDMP.K=TABHL(TEFDMP,RMNTMD.K,0,1,.2)

T TEFDMP=0,.58,.7,.83,.93,1

A RMNTMD.K=MTLOST.K/MAX(MTLND.K,.001)
```

We consider that we only need a requested flow of delivered material. In practice we have to consider three types of material: material with long lead time delivery, material in short supply and material fabricated in cycling. The factor RMNTMD is equal to 1 when the progress of procurement is 10% greater than the progress of the construction

6- the effect of overtime on construction (EFOVTC):

When we have an extended workweek, the increase of the progress rate will be lower than the overtime increase (see figure 14). The productivity loss adjusment applies to total manhours and not to the additional overtime hours. It is known that selection or spot overtime does not normally decrease the productivity:

```
A EFOVTC.K=TABLE(TEFOVT,RONHWC.K,0,0.80,.2)((NHWC+OVRTHC.K)/NHWC)

T TEFOVT=1,0.90,0.83,0.75,0.68

A RONHWC.K=OVRTHC/NHWC

A OVRTHC.K=TABHL(TOVRTC,RRFSCC.K,0,2,.5)*TESTOV

T TOVRTC=0,0,0,0,20

C NHWC=40, TESTOV=0
```

NHWC: Normal Hours per Week in Construction = 40

OVRTHC: OVeRTime Hours in Construction

RONHWC: Ratio Overtime hours to Normal Hours per Week in Construction

THE PROCUREMENT SUBSYSTEM

When the management decides to start the procurement process (PROCST), requisitions of material (REQMTL) are submitted in regard to the potential number of requisitions which is a function of the design progress (PRMTL); then purchase orders of material (MTLODR) are issued to the vendors who will prepare shop drawings for approbation by the engineers before starting the fabrication. In consequence, the quality of design of shop drawings (QDSD) will affect the delay of delivery of material and could postpone the duration of the construction. The quality of shop drawings is also a function of the average quality of design (AQD) prepared by the consultants (see figure 7 and table 1).

We have assumed that the material delivered on site must be 110% of the construction progress in such a way that if the real quantity of material on site (MTLOST) is less than the theorical quantity of material needed (MTLND), there will be a reduction of the apparent productivity (APRODC) and of the quality of the construction (QC):

THE BASE CONSTRUCTION SIMULATION (see figure 8 and table 2)

We have used the conventional construction scheme (we complete the design before to start the construction at week 144) as the base simulation.

We have started the procurement 24 weeks before the start of the construction and 120 weeks after the start of design. The schedule completion date for construction initially was 384 weeks. After the simulation, the construction finished date is week 417, 33 weeks more than the initial schedule. The cost of human resources is 359 million $.

THE FAST-TRACK CONSTRUCTION SIMULATION (see figure 9)

In the fast-track construction simulation, the construction is completed 55 weeks in advance of the conventional construction base simulation for an additional cost of four million $.

The negative effect is that we have rework during the construction because we construction starts 56 weeks before the completion of design. We have chosen to start procurement 30 weeks before the construction start to have an advance on procurement to be able to order enough material and taking into account material delay deliveries.

We will adopt the fast-track policy to compare three particular cases: the conventional construction with fixed schedule policy, the conventional construction with a ceiling on design resources plus a fixed schedule policy on construction, and finally a fast-track with fixed schedule policy with a ceiling on design workforce (see table 3).

COMPARISON OF A FAST-TRACK, WITH THE CONVENTIONAL CONSTRUCTION WITH FIXED SCHEDULE POLICY (see figure 10)

The conventional construction with a fixed schedule policy has a duration of 388 weeks, this is 26 weeks more than the fast-track construction for a cost of two million $ less than the fast-track. The saving could represent up to 30

TABLE 2: MODEL PARAMETERS FOR BASE SIMULATION

ASIDYC	ASsimIlation DelaY of Workers in Construction	4 workable weeks
CHIRDY	Construction HIRing DelaY	2 workable weeks
CONSST	CONStruction Start Time	144
DELYF	DELiverY Factor for material needed on site	1.1
DRSS	Delay to Recognize Schedule Situation	6 workable weeks
GPRODC	Gross PROductivity in Construction	0.208 job/ man/week
GPRODD	Gross Productivity in Design	0.208 drawings/ man/week
IW	Initial Work	8,000 drawings
ORDY	ORder DelaY of material	4 workable weeks
OVRTHC	OVeRTime Hours in Construction	0 (hours)
PROCST	PROCurement Start Time	120
RCD	Ratio Construction to Design man-hours	6
SCDCN	Schedule Completion Date for Construction iNitially	384 workable weeks
SCDND	Schedule Completion Date iNitially for design	144 workable weeks
WA	Work Added	0 (drawings)

	Const. Start Time (manhour)	Proc. Start Time (weeks)	Initial Work (drawings)	Design Finish Time (weeks)	Const. Finish Time (weeks)	Manhour Cost $
Conventional	144	120	8,000	146	417	$359E6
Fast-track	90	60	8,000	146	362	$363E6
Conventional with fixed schedule policy	144	120	8,000	146	388	$361E6
Conventional with ceiling on design & fixed-sche. policy	144	120	8,000	146	389	$360E6
Fast-track with ceiling on design work force & fixed schedule	50	5	8,000	146	273	$369E6

TABLE 3 : MANHOUR RESOURCES (DESIGN & CONSTRUCTION) COST COMPARISON

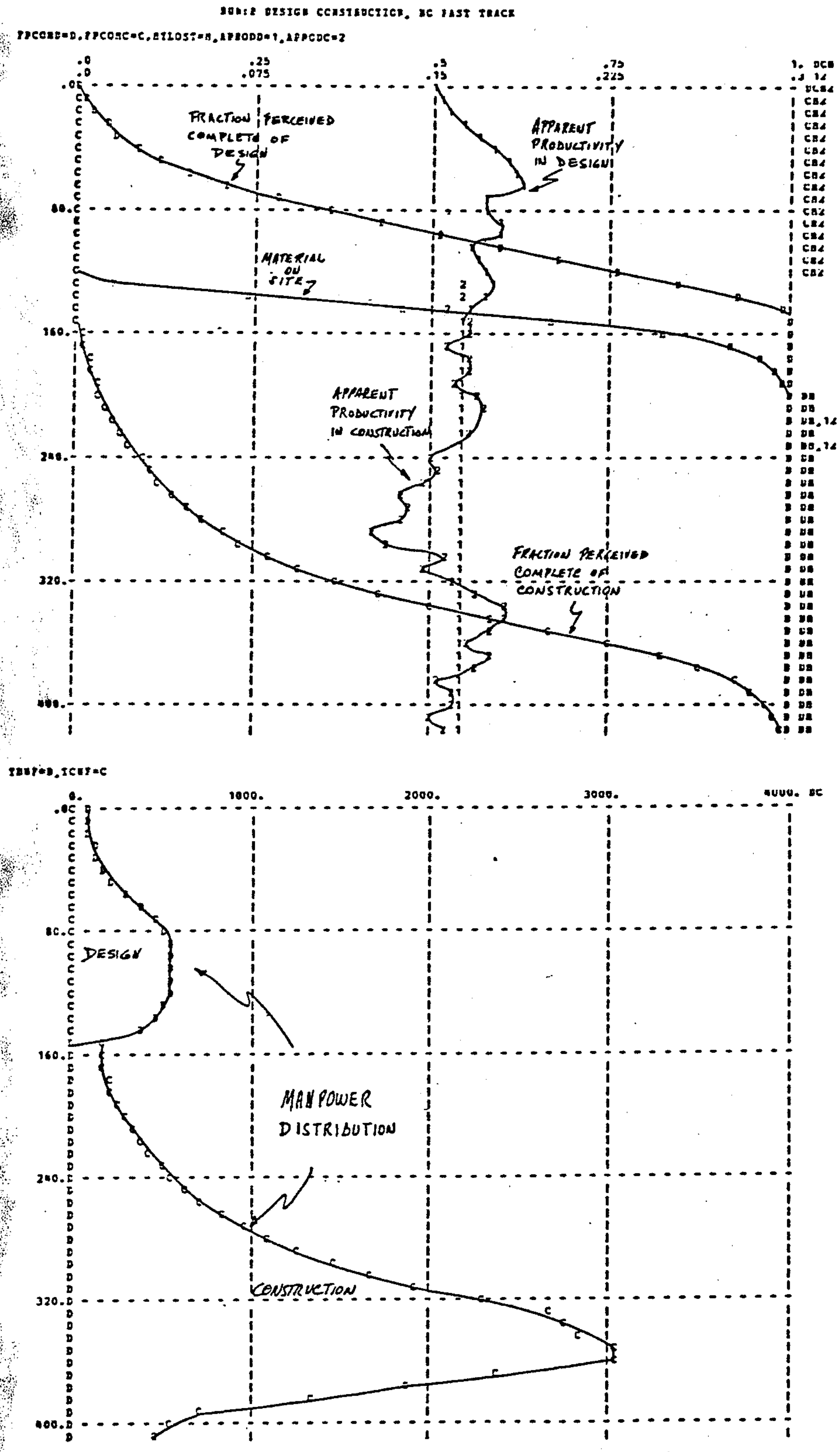
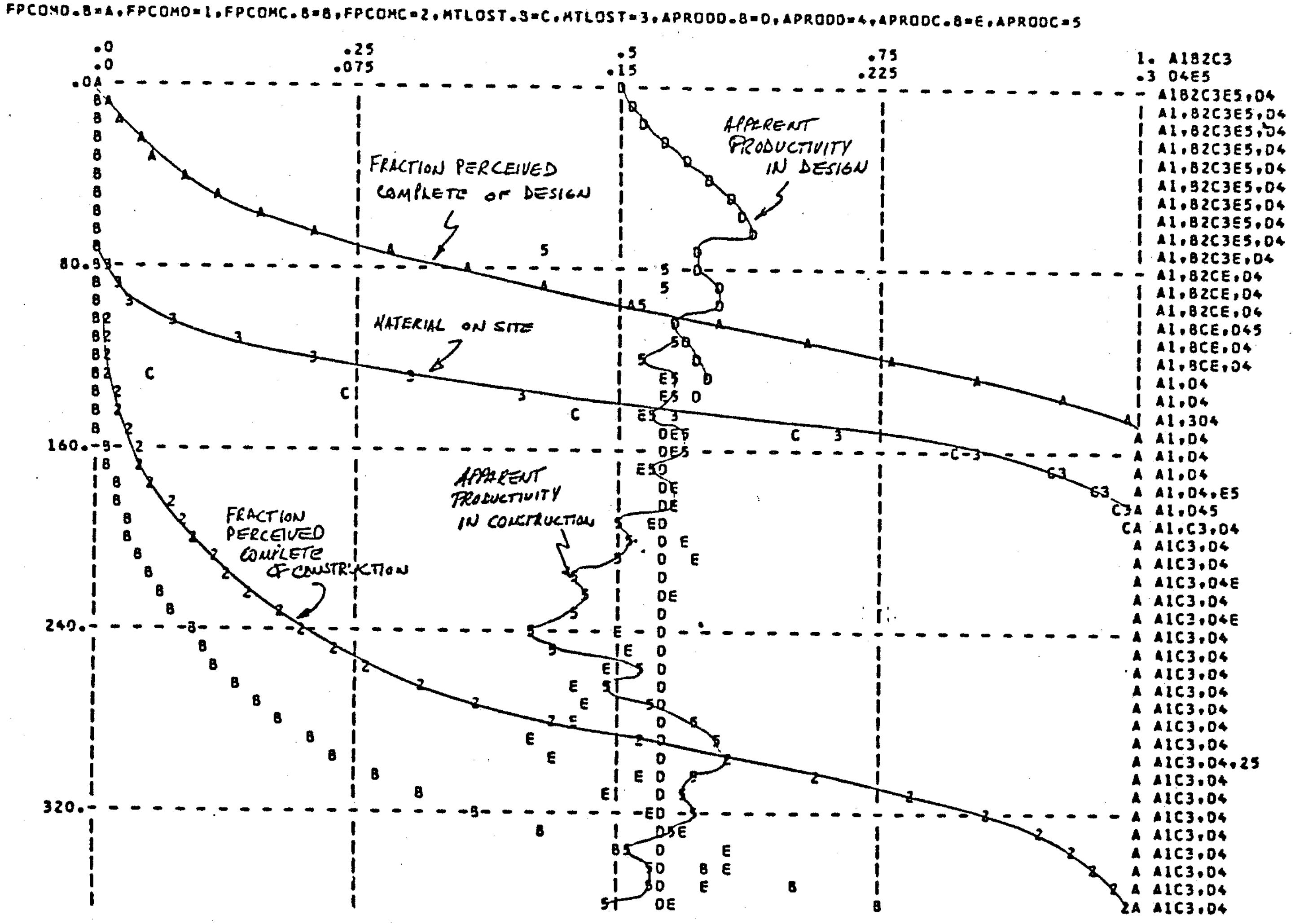


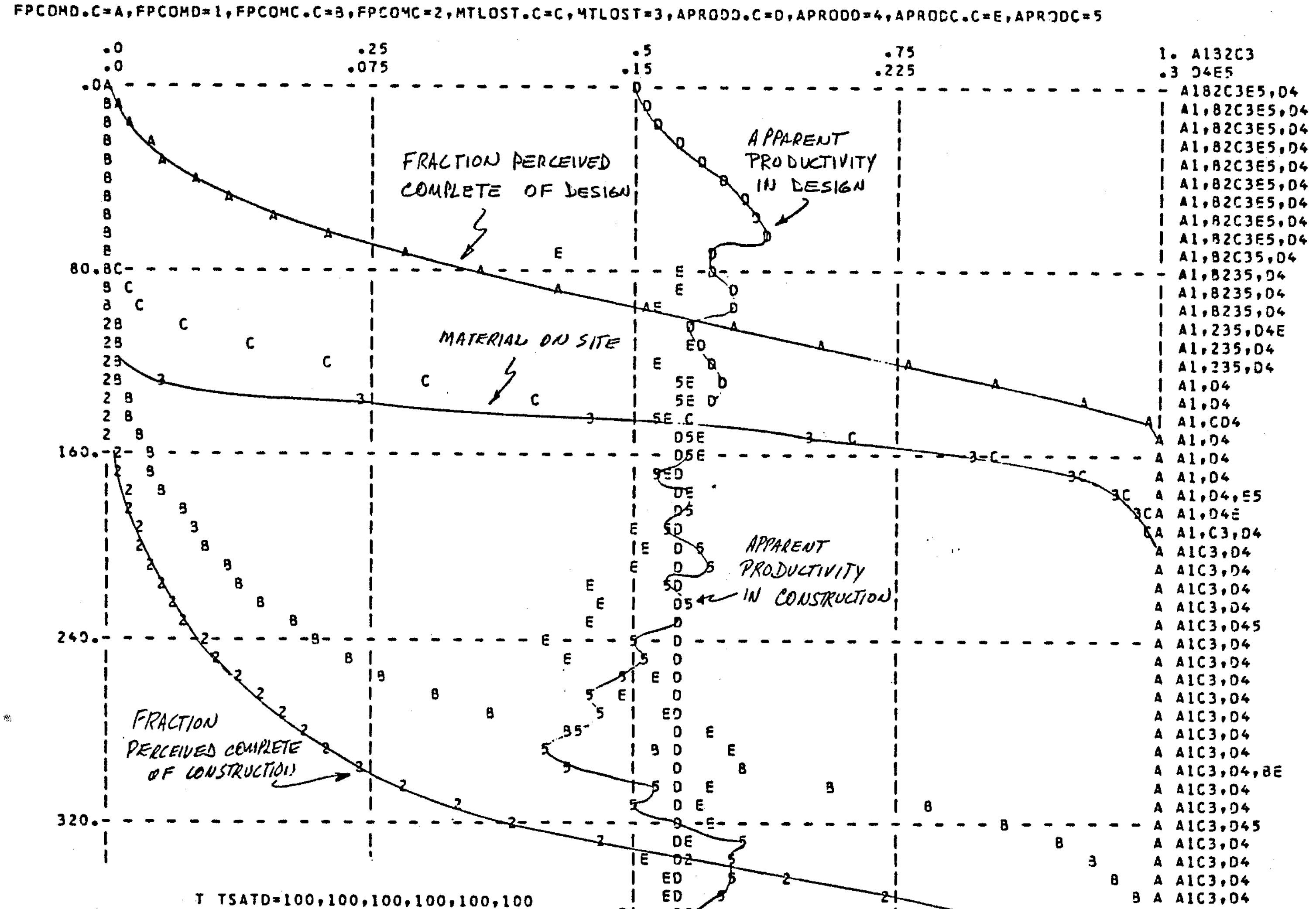
FIGURE 8: BASE CONSTRUCTION SIMULATION (CONVENTIONAL)



```
C SCDCN=330
C CONSST=90,PROCST=60

            CONSST  PLTPER  PROCST  SAVPER   SCDCN
PRESENT       90.      8.     60.      8.    330.
ORIGINAL     144.      8.    120.      8.    384.
```

FIGURE 9: FAST-TRACK CONSTRUCTION SIMULATION



```
T TSATD=100,100,100,100,100,100
T TSATC=200,200,200,200,200,200

          TSATC(1)     (2)     (3)     (4)     (5)     (6)
 PRESENT    200.      200.    200.    200.    200.    200.
ORIGINAL     20.       20.     10.      6.      4.      3.

          TSATD(1)     (2)     (3)     (4)     (5)     (6)
 PRESENT    100.      100.    100.    100.    100.    100.
ORIGINAL     20.       20.     12.      8.      5.      4.
```

FIGURE 10: COMPARISON OF A FAST-TRACK CONSTRUCTION, WITH THE CONVENTIONAL CONSTRUCTION WITH FIXED SCHEDULE POLICY

million constant $, assuming that the rental revenue is collected to reach a maximum revenue of approximately 10% of the total cost after four year.

COMPARISON OF A FAST-TRACK, WITH A CONVENTIONAL CONSTRUCTION WITH A CEILING ON DESIGN RESOURCES, PLUS FIXED CONSTRUCTION SCHEDULE POLICY (see figure 11)

The design resources are limited at 300. On account of limited resources, the design will take longer and will be completed at week 230, 86 weeks later than originally scheduled. During that period of time, because construction has started, undiscovered drawings that need reworks are discovered and generate additional work on the field.

In this solution, we see that the productivity and quality go down in the period of overlap between design and construction. This is a conventional construction that becomes fast-track on account of the limited resources. It costs three million $ less than the fast-track and finishes 27 weeks later. We can estimate that the ordinary fast-track construction represents an additional rental revenue up to 37 million constant $.

COMPARISON OF A FAST-TRACK, WITH A FAST-TRACK THAT HAS A FIXED AND CRASHED SCHEDULE POLICY AND A CEILING POLICY ON THE DESIGN WORKFORCE (see figure 12)

We compare an ordinary fast-track (with no policy to control schedules) with a crashed schedule fast-track (with a policy to control schedules), where we start procurement 5 weeks and construction 30 weeks after the beginning of design. We slip only by two weeks the end of design and by three weeks the end of construction that finishes at week 273, 89 weeks earlier than the ordinary fast-track construction scheme for an additional labor cost of six million $.

The additional revenue generated by the crashed, fast-track and fixed schedule construction could be up to 100 million constant $. This alternative illustrates why in major projects it is economic to take the risk of loosing millions at the front end to crash a project, at the expense of reworks to save hundred of millions.

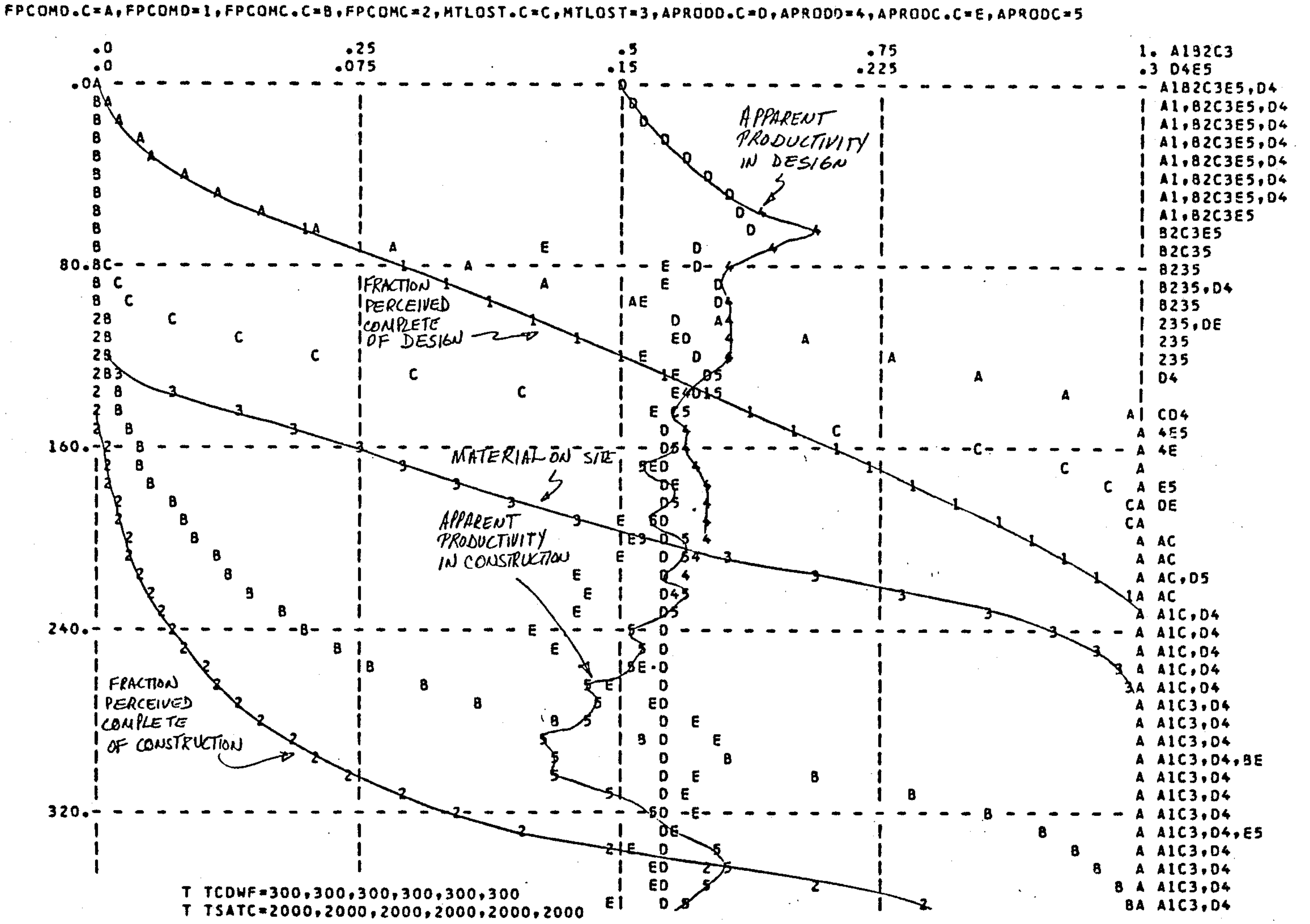
CONCLUSION

Is the crashed fast-track construction of major projects really on the long term the most economical procedure?

The above question was raized in the conclusions presented by Jean-Claude Huot at the First International Colloquium in French on Major projects in May 1981 and this paper is part of the answer.

A MACRO-Engineering Center regrouping four Monteal universities has been created by one of the authors of this paper in 1984 to assist the universities in doing further researches on that subject.

At an important colloquium organized on March 1985 by the Large Scale Program Institute of the University of Texas at Austin, an interesting query came from the assistance to find out about existing researches on the effect of delaying design in major projects. This will be answered with a more elaborate system dynamics model taking into account all the economical factors (such as escalation, interest on borrowed money, capitalization, internal rate of

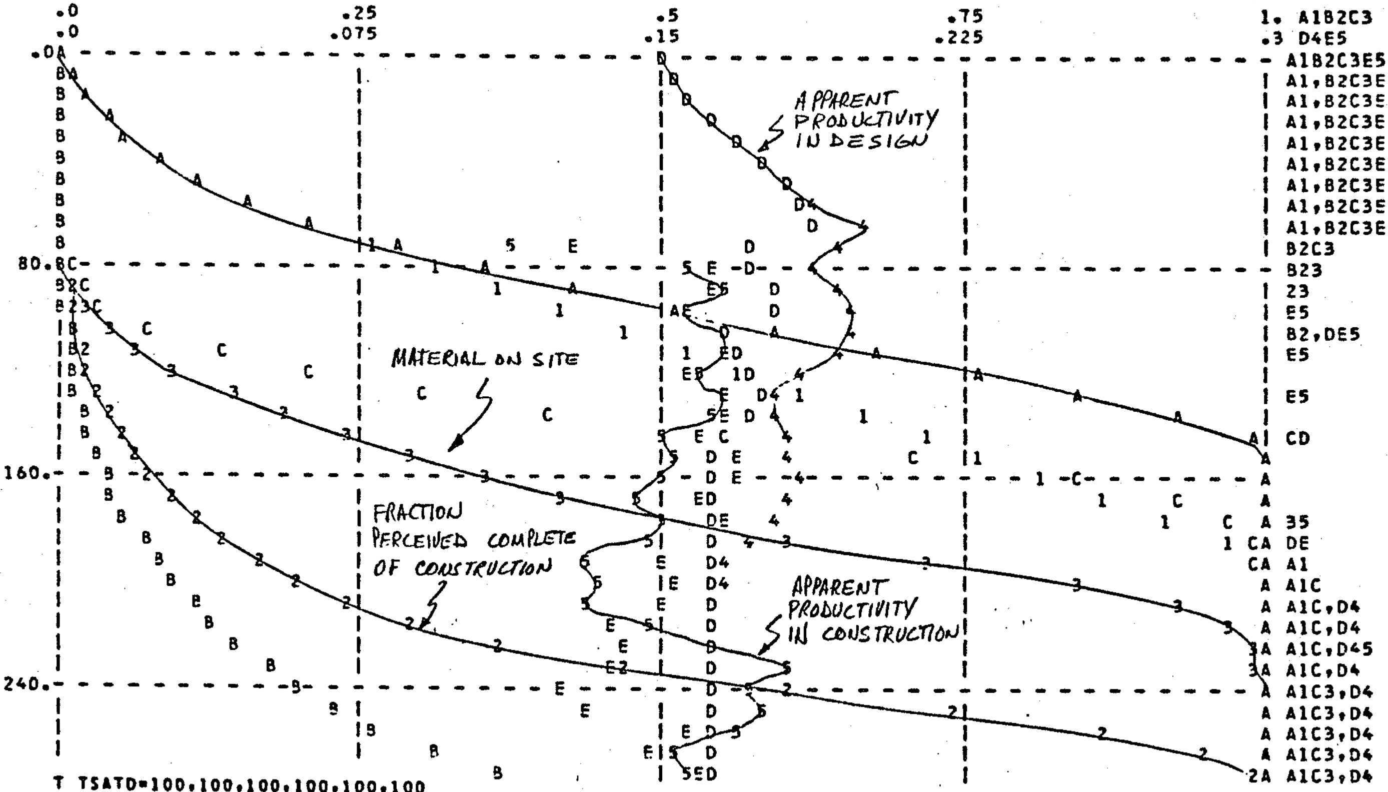


```
T TCDWF=300,300,300,300,300,300
T TSATC=2000,2000,2000,2000,2000,2000
          TCDWF(1)     (2)     (3)     (4)     (5)     (6)
 PRESENT     300.     300.    300.    300.    300.    300.
ORIGINAL    2000.    2000.   2000.   2000.   2000.   2000.

          TSATC(1)     (2)     (3)     (4)     (5)     (6)
 PRESENT    2000.    2000.   2000.   2000.   2000.   2000.
ORIGINAL      20.      20.     10.      6.      4.      3.
```

FIGURE 11: COMPARISON OF A FAST-TRACK, WITH A CONVENTIONAL CONSTRUCTION WITH A CEILING ON DESIGN RESOURCES PLUS A FIXED CONSTRUCTION SCHEDULE POLICY

```
FPCOMD.C=A,FPCOMD=1,FPCOMC.C=B,FPCOMC=2,MTLOST.C=C,MTLOST=3,APRODD.C=D,APRODD=4,APRODC.C=E,APRODC=5
```



```
T TSATD=100,100,100,100,100,100
T TCDWF=350,350,350,350,350,350
T TSATC=2000,2000,2000,2000,2000,2000
C CONSST=30,PROCST=5
C SCDCN=270
            CONSST   PLTPER   PROCST   SAVPER    SCDCN
 PRESENT       30.       8.       5.       0.     270.
ORIGINAL      144.       8.     120.       8.     384.

          TCDWF(1)      (2)      (3)      (4)      (5)      (6)
 PRESENT      350.     350.     350.     350.     350.     350.
ORIGINAL     2000.    2000.    2000.    2000.    2000.    2000.

          TSATC(1)      (2)      (3)      (4)      (5)      (6)
 PRESENT     2000.    2000.    2000.    2000.    2000.    2000.
ORIGINAL       20.      20.      10.       6.       4.       3.

          TSATD(1)      (2)      (3)      (4)      (5)      (6)
 PRESENT      100.     100.     100.     100.     100.     100.
ORIGINAL       20.      20.      12.       5.       5.       4.
```

FIGURE 12: COMPARISON OF A FAST-TRACK CONSTRUCTION, WITH A FAST-TRACK CONSTRUCTION THAT HAS A FIXED AND CRASHED SCHEDULE POLICY AND A CEILING POLICY ON THE DESIGN WORKFORCE

return on investment, etc.), and will constitute the next phase of our researches.

In a period of declining growth, on account of the economy of scale on high interest rates and inflation, there are indisputable avantages for crashing the schedule to a maximum and to start the construction as soon as possible, even at the expense of productivity, quality and project team morale. This is going usually to be the solution retained by a management motivated only by the maximization of profits on the short term. But we believe that system dynamics can help us to find another solution, a long term solution, that maximizes not only economics but also quality, productivity and human resources.

We have chosen a building of 250 floors, a major building of a dimension not achieved yet, to illustrate the dilemma of size that we face with MACRO-Engineering Projects. The tendency to crash major projects with fixed schedule policy and strong management teams is dependent of the political and economical survival of the project itself. Major Projects too often fail and become Mega-Project Disasters; this has been brillantly demonstrated by O.P. Kharbanda and E.A. Stallworthy and has been one of the preoccupation of the Major Projects Association of U.K.

We see that there are definitely three major problems in crashing a major projects, a problem of quality, productivity and morale. It is obvious that poor quality and productivity have a bad influence on employees' morale. Rework is no good for workers, nobody likes to build for the sake of demolishing, it is a vicious circle that keeps generating poor quality and bad productivity. It kills the initiative and ingenuity that have been so important for the innovative and competitive contractors.

Because we are bound to build MACRO-Engineering Projects in the future that will support the next Kondratieff long wave, as predicted by Dr Frank P. Davidson of M.I.T., we have to investigate further the dynamics of large scale programs and the strange economics that they generate to avoid mega-project disasters. For every unusual major project, it should be mandatory to develop, at first, a system dynamics model to test its limits.

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