CIVIL ENGINEERING DESIGN MANAGEMENT USING A SYSTEM DYNAMICS MODEL

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ABSTRACT

In an attempt to understand the current practices and problems in design projects, a system dynamics model was developed for the management of detailed design process in of a civil engineering project. The model took an integrative approach, consisting of four interrelated subsystems: human resources, design production, controlling and planning. Two sets of data were used to initialise and test the model. Some policies and scenarios were then explored to gain insight into the model's behaviour and to seek alternatives for better management.

The experimentation showed the following policy hierarchy:

- In terms of meeting scheduled time, the effectiveness of policies is in the order: (1) progress control, (2) manpower allocation, (3) estimation of workload, and (4) realisation of underestimated work.

- In terms of man-days expended or cost reduction, the effectiveness of policies is in the order: (1) manpower allocation, progress control, (3) estimation of workload, and (4) realisation of underestimated work.

As such, good estimation of workload is essential but not sufficient to bring the project to finish on schedule. Good project control and early perception of real progress are needed to ensure adequate resource allocation and on-time completion.

INTRODUCTION

Engineering design is done in two major phases: (1) preliminary design; and (2) detailed engineering design. Preliminary design stresses architectural concepts, evaluation of technological process alternatives, size and capacity decisions, and comparative economic studies. In detailed design, the process becomes more formalised, having more specific steps with less random interactions. It involves successively breaking down, analysing and redesigning the structure and its elements so that it complies with standards and produces drawings and specifications needed for site construction. It also involves the integration of the efforts of people with different specialisations. The problems of design, as for all stages of project management, are to meet cost, time and quality requirements.

While system dynamics has been applied to general project management by Richardson and Pugh III and the management of site construction by Chang, et al, (1991), its application to design is limited to a specific application for a building construction project by Huot and Sylvestre (1985). Their model was designed for strategic project management focussing specifically on fast-tracked projects. This paper reports on a model constructed for general application to the detailed design stage of a civil engineering project.

ENGINEERING DESIGN MODEL

Engineering design can be viewed as a system consisting of different components or subsystems which are interrelated. These subsystems are human resource, design productions (drawings, specifications and bills of quantities), controlling and planning. The model is a modification of Abdel-Hamid and Madnick's (1991) software development model. The design model is constructed on the premise that a design firm will first agree needs and timing with the owner and then proceed to decide how to manage the project to facilitate completion within the agreed time.

Simplified feedback loops of the model is shown in Figure 1. It consists mainly of three loops. The first is a goal seeking or negative feedback loop with three stocks. The goal is the indicated workforce to finish the project within the scheduled time. The second loop is also a negative feedback loop with three stocks. The loop determines how productivity is perceived and the job size (work load) is adjusted. The third loop is a positive feedback loop with three stocks. It controls how schedule date is maintained or adjusted based on the workforce level available and resistance to changing schedule date. A detailed explanation of the model construction is available elsewhere (Lim, 1994).

Detailed structure has been developed for (1) the human resources management subsytem (Figure 2); (2) the design production subsytem: having manpower allocation sector, design development sector and rework sector; (3) the controlling subsystem (Figure 3); and (4) the planning subsytem (Figure 4). Only the design production subsystem is explained here.

Civil engineering design production starts with analysis of preliminary estimated dimension and is followed by refinement through successive iterations to seek the optimal dimension and compliance with standards. The result of calculation is then transformed to

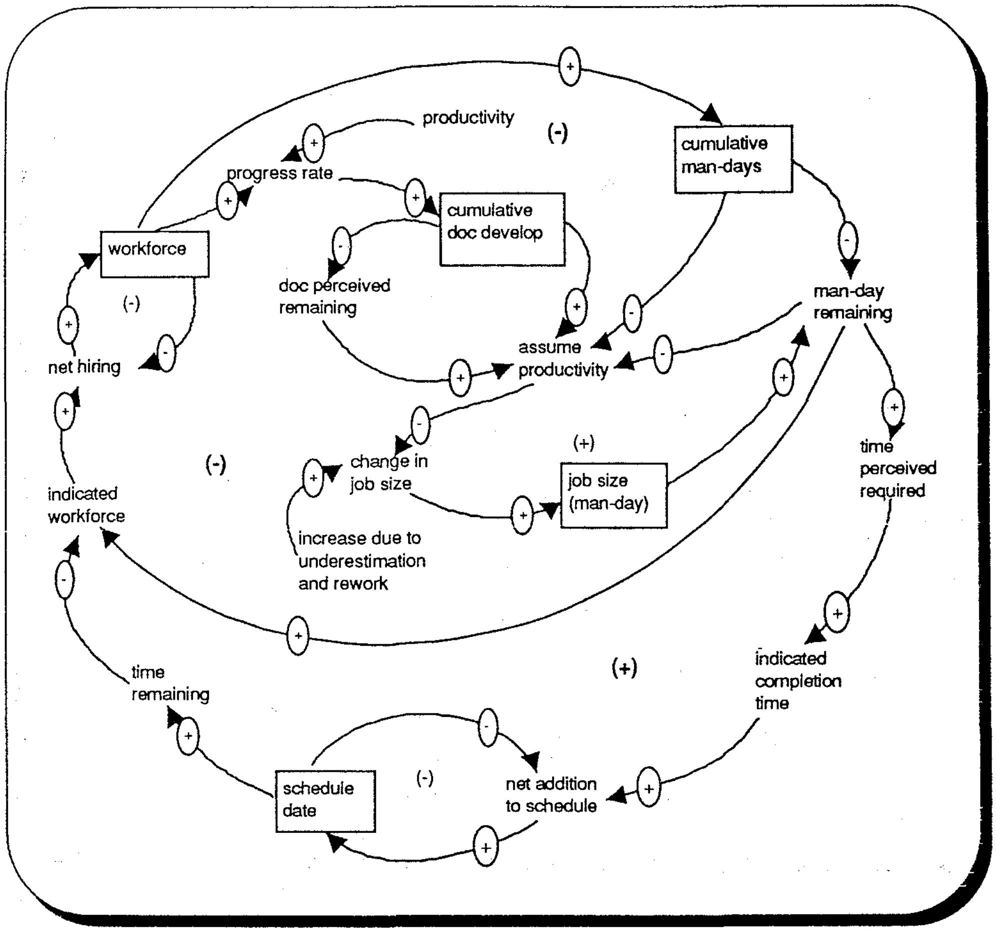

Figure 1: The major feedback loops of the design project model

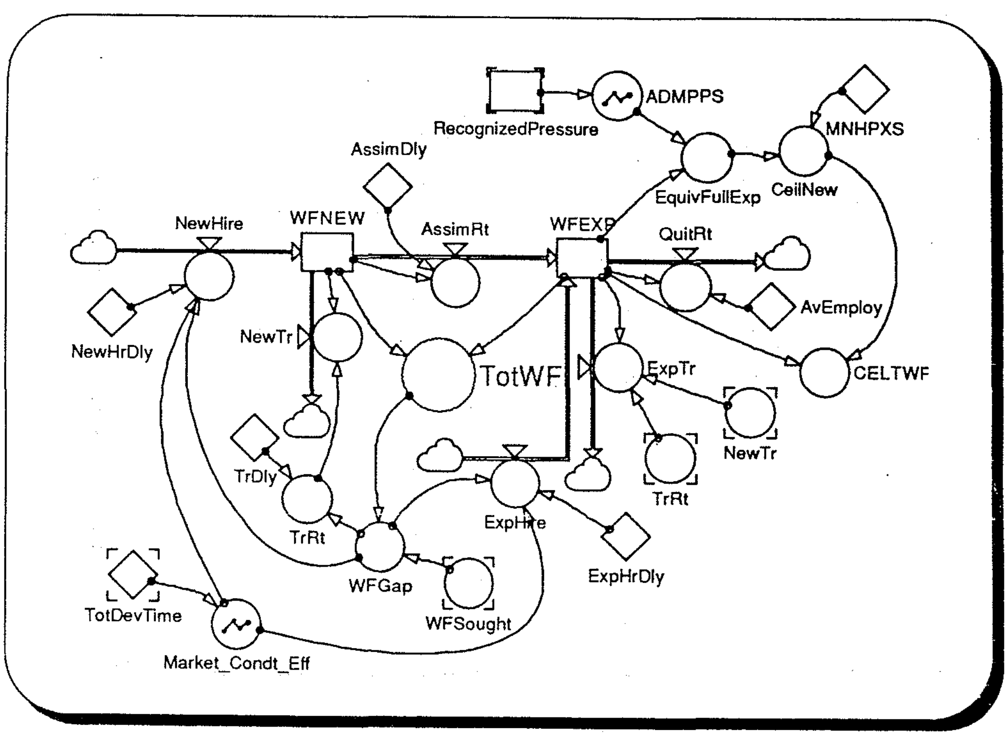

Figure 2: The human resources subsystem

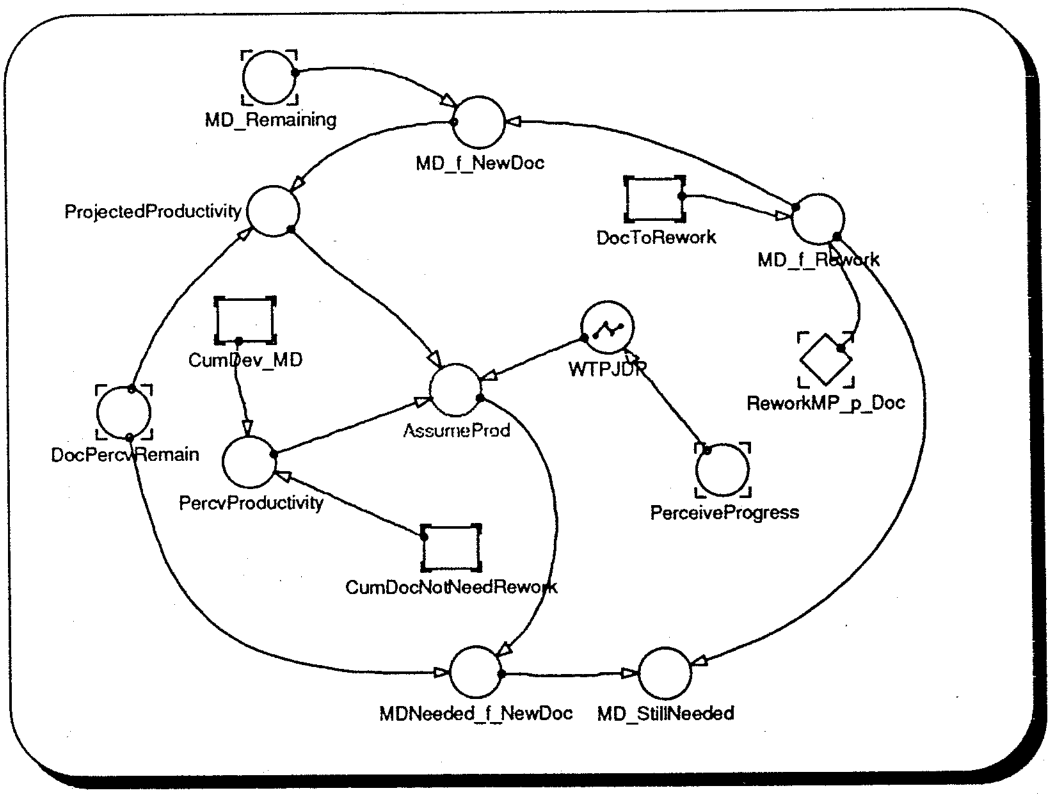

Figure 3: The controlling subsystem

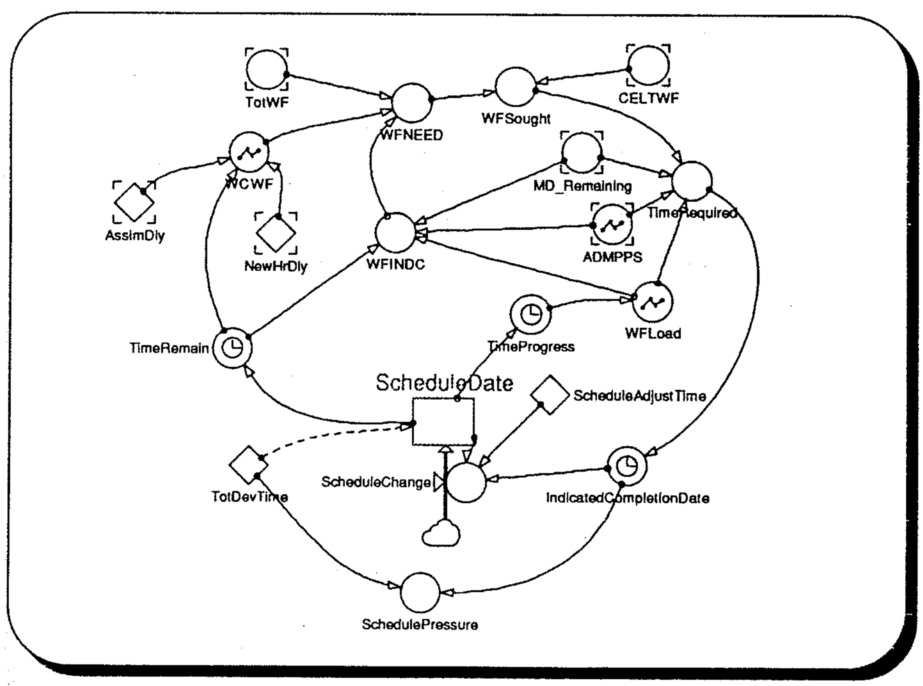

Figure 4: The planning subsystem

drawings and specification documents for site construction. When calculations are being made, there is usually no effort expended for checking. As such, quality assurance is done on drawings only. Errors in drawings may however be traced to design calculation.

DATA ANALYSIS

Data needed to run the model include total planned duration, planned manhours/days, planned manpower loading, total documents produced, average design productivity (documents per man-day), amount of rework, and effort spent for checking and rework. Additonal qualitative data include task distribution effect, communication losses, effect of shedule pressure on overtime, etc., They are based on senior engineer's judgment. The model, as developed, is aimed at projects with duration long enough to allow for hiring and attrition and having about 10 or more design staff.

The two projects used for testing the model are referred to in this paper as the WWR project and the AFBC project. The WWR Project covers the preparation of masterplan for an area of 86.5 sq. km. of which 16.95 sq. km. are subject to detailed design of drainage, sewerage and waste water treatment systems in Rayong Province, Thailand. The AFBC project is an engineering procurement contract for natural gas compression in Indonesia. It covers design, procurement of equipment and materials, installation of gas gathering, separation, dehydration and compression plant.

The result of the base run using data from the two projects are shown in Table 1. The results show fairly good agreement between actual results and thus confirms that the model provides a good replication of reality.

Table 1: Actual result versus model output

WWR Project	Actual	Simulated Base run
Cumulative work-days	4,554 (with overtime 723 days)	4,588 (with overtime 358 days)
Scheduled completion time	220 days	218 days
Effort for checking & rework	10% (455 work-days)	7% (311 work-days)
Peak workforce level	56 people (around day 176-198)	48 people (at day 174)
AFBC Project		
Cumulative work-days	21,286 (no overtime data)	20,896 (with overtime 710 days)
Scheduled completion time	Not available (268 planned)	282 days
Effort for checking & rework	10% (2,128 work-days)	11% (2,240 work-days)
Peak workforce level	114 people (around day 100-125)	90 at day 240

POLICY ANALYSIS AND DESIGN

Parameter changes

Parameter changes that can be experimented with are listed below.

1. The number of projects a design team member can be involved in at the same time.
2. Time required by a new member to fully understand the project. This can be improved through training.
3. Overtime usage.
4. Time delay in effecting corrections to drawings.
5. The willingness or reluctance to adjust schedule which may be limited by contract.
6. The spead of project activities. Usually parallel activities are more doing the peak of the project.
7. Discovery of understimation which may be due to unanticipated changes but can be effected through scope definition and contract arrangement.
8. Willingness to change workforce effected via hiring policy.
9. Accuracy of productivity assessment.

Structural changes.

The base run for the model replicates normal practice very well. Howerver, it contains flaws inherent in design management practice such as underestimation of work, misperception of progress and rework. The policy changes experimented with are listed below and the results shown on Table 2.

1. Good estimation of project scope. This is effected by setting the value of undestimation fraction to zero. The result (Table 2) showed a better performance in reducing duration and leveling of workforce. Absence of undestimation reduces changes to scope and additional efforts are needed only to correct drawings. Overtime use can be reduced and sudden changes to workforce eliminated. This accords with project management literature (Birnberg, 1992 and Oberlender, 1993 for example).

2. Good control of work progress. This is possible if there is a good perception of real progress. In the model, it is implemented by making assumed development productivity, a value used to adjust job size, to be more of perceived productivity than projected productivity. The result showed significant improvement (Table 2). improved progress assessment can be achieved through better measurement method to reflect real progress rate of time, cost (man-hour), and work.

3. Combined policy of good estimation and progress control. It showed significant improvement and removes overtime use as schedule pressure is eliminated.

4. Quicker realisation of underestimated work. This means that additional tasks are discovered at a faster rate and after 60% progress, there are no addtional tasks. The change improved project baselines, as management will be able to make better workforce arrangement for the project.

5. Staffing policy is critical to schedule attainment. In design management, a schedule date is established, man-hours are then estimated, and the project staffing is decided. The obvious problem is to keep the staff as small as possible to minimise overhead and communication losses while meeting the schedule. Options may include: overtime work, contract staff, increasing permanent staff and using CAD systems to reduce drafting and engineering time. The policies implemented are listed below.

(i) No overtime policy. This resulted in schedule slippage but reduced cummulative mandays. This implies that the extra time spent in the base run to speed up project is due to overtime.

Table 2: Comparison of different policy runs

No.	Simulations	WWR Project	AFBC Project
1.	Base run	4,588 work-days (incl. 368 days overtime); 218 days	20,896 work-days (incl. 710 days overtime); 282 days
2.	Good Estimation	4,529 work-days (incl. 168 days overtime); 208 days	20,878 work-days (with 515 days overtime); 279 days
3.	Good progress control	4,453 work-days (incl. 45 days overtime); 201 days	20,596 work-days (incl. 1.37 days overtime); 268 days
4.	Good estimation and good progress control	4,474 work-days (no overtime); 198 days	20,688 work-days (incl. 1.35 days overtime); 268 days
5.	Quicker realization of underestimated work	4,543 work-days (incl. 179 days overtime); 209 days	20,700 work-days (incl. 542 days overtime); 279 days
6.	No overtime	4,369 work-days; 223 days	20,493 work-days; 285 days
7.	Manpower allocation	4,409 work-days; 205 days	-

(ii) Manpower allocation policy. This concerns the number of projects a member of staff is allocated to. While some companies allocate staff to one project only, pressure of time and design priorities and manpower availability may force some companies to move staff around projects. The result for one project showed that assigning staff to one project only significantly improves performance as assimilation is better.

Scenario Analyses

SD modeling allows management to experiment with possible senarios during the implementation of a project. The analyses conducted are shown below.

Scenario 1. Shortage of experienced workforce. If it is impossible to staff project with experienced workforce, management needs to know how the use of new workforce will affect the project.

Scenario 2. Scenario 1 + manpower allocation policy. Shortage of experienced workforce forces management to use part-time workforce.

Scenario 3. Scenario 2 + sudden departure of xperinced workforce. This may happen in a very competitive market environment or any other reason.

Scenario analysis can enable design managers to manage by perception and thus prevent/reduce the need for crisis in a difficult project environment. The results from the simulations are shown below.

Run	Cumulative work-days	Scheduled completion (days)
Base run	4,588 (including overtime 368 work-days)	218
Scenario 1	5,223 (including overtime 640 work-days)	241
Scenario 2	4,916 (including overtime 284 work-days)	213
Scenario 3	4,988 (including overtime 327 work-days)	216

CONCLUSIONS AND FURTHER RESEARCH

A survey of 110 design practices in the U.S.A. (Birnberg, 1992) has identified 10 major concerns of design firms in order of frequency of mention as (1) making a profit/budget; (2) meeting shedules and deadlines; (3) change order and/or scope management; (4) internal communications; (5) quality control; (6) client communication; (7) lack of experienced staff and/or PMs; (8) low fees/determining fees; (9) planning/ scheduling; and (10) time management. A model of the design process has been constructed which incorporates most of the problems identified by Birnberg. The model replicates field practice well and has also been simulated to show that improvements can be made through policy changes. However, not all changes are beneficial. The results of experimentations with two design projects show the follwing policy hierarchy for meeting project deadlines: (1) good progress control; (2) efficient manpower allocation; (3) accurate estimation of workload; and (4) early realisation of underestimated work. If the goal of management is to reduce cost, then efficient manpower allocation is better than progress control.

SD modelling is a powerful tool for experimeting with possible, even extreme, scenarios in project management. It can uncover flaws in practices which in the short run may seem to improve performance but are not beneficial on the long run. Model experimentations can isoloate a system and show the effects of changes in real world situations. The model described has shown that civil engineering design can benefit much from SD modelling.

The model, as constructed, does not distinguish between drafters and designers. This needs to be improved through the segregation of the functions. The model also does not consider the efficiency of overtime usage. It should be possible from actual records to build efficiency considerations into the model. Finally, projects are managed at the firm level, it is desirable to expand the model for overall firm management.

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