MiDiCON: A Model for Mitigating Delays in Construction

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ABSTRACT: *Delays are an endemic feature of the construction industry. Typically, when a delay occurs in a project, the project manager often expedites progress through activity crashing with respect to available float and time-cost relationships. An accelerated schedule is thus obtained by either prescribing overtime working hours or procuring additional resources or a combination of both. However, excessively prolonged overtime work can generate quality problems, such as rework, and additional resources. There is therefore a need for a model to assist project managers with understanding the complex nature of attaining a trade-off between overtime working and the procurement of additional resources. In this paper, a system dynamics model for* ***MI****tigating* ***D****ays* ***i****n* ***CON****struction (MiDiCON) due to the effects of prolonged overtime work on project costs and quality is presented To overcome project delays, several options representing various combinations of prescribing overtime work and injecting additional resources are analyzed. Utility theory is then applied to determine the most appropriate solution for mitigating project delays.*

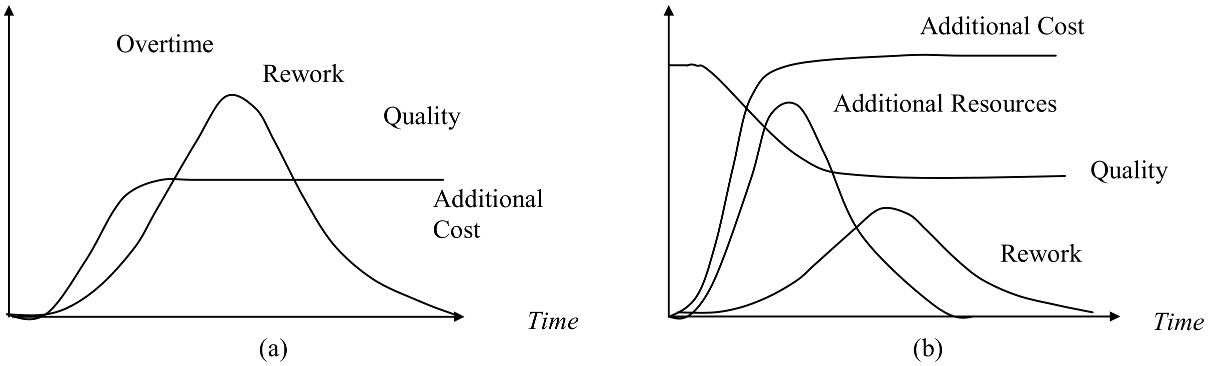
Keywords: Time, cost, quality, rework, overtime, activity crashing, systems dynamics, utility theory.

INTRODUCTION

Delays are an endemic feature of construction industries worldwide (Yogeswaran *et al*., 1997). Consequently, there has been a wealth of research that has investigated project delays and the reasons for possible time and cost overruns in construction (Majid and McCaffer, 1998). When a delay occurs, a project manager is often faced with two options: prescribing overtime work and injecting additional resources, in order to shorten (crash) the duration of certain activities. While injecting additional resources can significantly increase project costs, prolonged overtime working may cause declines in productivity and performance, which may also generate rework (Love *et al*., 1999). To understand how these options interact and determine a project's overall duration is complex because of the interdependency that exists between process variables. Numerous studies have investigated the impact of overtime work on project performance and productivity (Thomas and Raynar, 1997). These studies all concluded that excessive amounts of overtime work could cause declines in performance and work quality, and consequently increase rework. Conversely, injecting additional resources to a particular activity may crowd the workface, which will also negatively affect the productivity and performance. Thus, to understand the impact of activity crashing on project quality and productivity, there is a need to systematically analyze the impact it has on project cost and quality. In this paper, a system dynamics model for **MI**nimizing **D**elays **i**n **CON**struction (MiDiCON) due to the effects of prolonged overtime work on project costs, and quality is presented. Several options for mitigating project delays using overtime work and additional resources are analyzed and simulated. Utility theory is then applied to determine the most appropriate solution.

SYSTEM DYNAMICS

System dynamics is often used as methodology for improving the effectiveness of the decision-making process, and in recent times has become a popular technique for modelling change in project management (Rodrigues and Bowers, 1996). Before a system dynamics model is developed a reference mode needs to be established so as to calibrate the systems behavior. A reference mode is the graphical pattern of the problem over a period of time. A reference mode is used to create confidence in the model from both a structural and behavioral perspective. Using data derived from research undertaken by the authors (Love *et al*., 1999), and previously published literature reference modes for overtime working and additional resources have been developed and can be seen in Figure 1.



(a) (b)

Figure 1: Reference Modes for (a) Overtime Working, and (b) Additional Resources

Figure 1a indicates that overtime working initially has a negative effect on a project's quality. After a period of time this then stabilizes at a level, which is lower than the initial expected quality level. From a system dynamics perspective, this process is known as *goal adjustment* and is considered to be a factor that contributes to the occurrence of rework in projects (Love *et al*., 1999). The additional costs that are incurred from overtime working can also be identified in Figure 1a. From Figure 1b, it is indicated that injecting additional resources increases the overall project cost as compared to the overtime-working mode, which results in less rework being perceived. To examine the combined effect of prescribed overwork and additional resources in activity-crashing, the authors have developed a system dynamics model to simulate the relationships among the key variables that are considered to be important for activity-crashing: additional cost, cumulative work scope, quality and rework.

MODEL DEVELOPMENT

In a previous study the authors had identified key process variables that significantly impact project performance during activity crashing (Love *et al*., 1999). In this study more variables with significant impact on project performance during activity crashing were identified from the literature. The causal relationships that exist among the variables were examined by developing a causal loop diagram illustrated in Figure 2 using the ITHINK software package. A causal loop diagram is used to identify the cause-effect interactions, or feedback loops, among selected variables. Round rectangles represent selected sectors. The model consists of seven sectors, namely, *progress*, *scope and rework*, *overtime and additional resources*, *cost*, *quality*, *human resource* and *fatigue and motivation*. The thick straight lines identified in Figure 2 are the dynamic interactions among sectors, which indicate the high-level map of the system dynamics model. The model is initialized to the situation where actual project progress is equal to the desired progress so there is no need for activity crashing. The structure of the model is large and consists of 100 basic building blocks and as a result only the simulation results are presented in this paper.

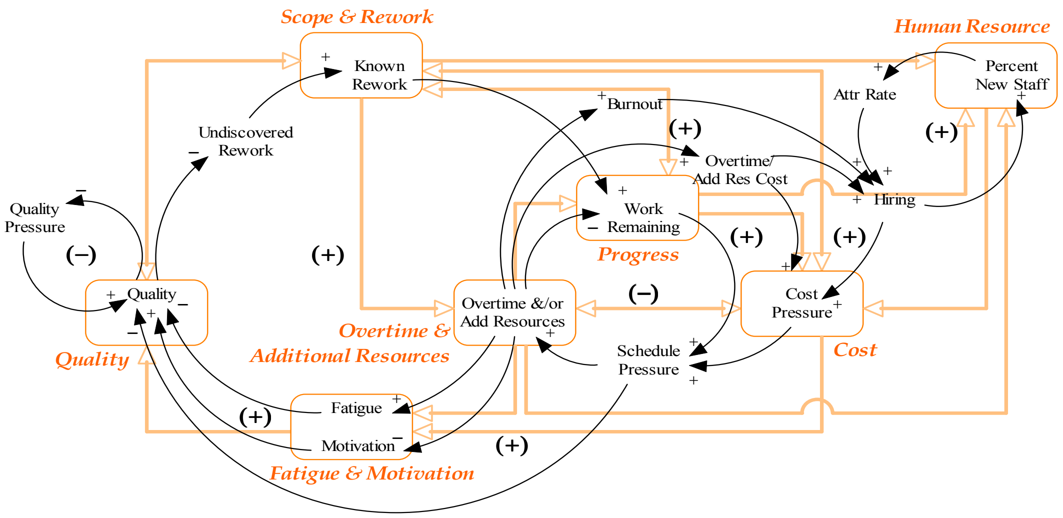


Figure 2. The dynamic interactions between the model sectors

Figure 2 suggests as the work remaining in the current project increases, it will generate schedule pressure. This schedule pressure may force the project manager to prescribe overtime works and/or inject additional resources in to reduce the amount of work remaining. However, sanctioning overtime and/or injecting additional resources may cause declines in quality, which can result generate rework.

MODEL SECTORS

In the *scope and rework* sector, as shown in Figure 3, schedule pressure is defined as a non-linear graphical function of schedule discrepancy and budget inadequacy. Parameter schedule discrepancy is the difference between desired progress and actual progress at the job site, while budget inadequacy is deemed to be the ratio of the difference between available budget and required budget over the required budget. Work scope accumulated due to schedule discrepancy and rework generated is drained through work outflow. The impact of schedule pressure on quality is modelled in the *quality sector*. This sector simulates the decline of quality when the pressure to expedite the project increases. In the *overtime and additional resources* sector, the parameter schedule pressure generates the need for prescribing overtime working and/or injecting additional resources. Thus, additional resources increases a project's cost, and prescribing overtime work affects cost, schedule, additional recruitment of human resource, personnel burnout, motivation and fatigue. The *progress* sector simulates desired progress based on the scope of work, actual progress as a result of normal and overtime working hours and their difference. The *cost* sector keeps track of the available budget from project revenues and required budget for resources. Additional cost is defined as the difference in the required budget and available budget. Similarly, the *human resource* sector simulates the inflow of additional human resource requirements caused by prescribed overtime works and personnel burnout. The changes in the levels of fatigue and motivation of personnel were modeled in the *fatigue and motivation sector*.

MODEL VALIDATION

Model validation is undertaken to ensure the soundness and usefulness of model. Validation requires not only that the model meets with known 'physical laws', but also that its results comply with the behavior of the real world. Thus, the model was tested for both from structural and behavioral validity according to the guidelines described in Forrester and Senge (1980). In addition, it has been examined for structural validation inasmuch as the major factors identified in Love *et al*. (1999), and from the literature have been used and the values used in the model derived from completed projects. The model was tested for behavior prediction so as to assist practitioners with particular scenarios they may be faced with. To simulate the model for a base run it was calibrated to replicate the delay process according to data collected from 14 projects in Hong Kong. These projects are all Harmony Type 1, which is a standardized modular design adopted by the Hong Kong Housing Authority (HKHA 1989/90). Of the 14 projects, 8 projects contained activity-crashing data, as they were used to generate the non-linear time-cost curves. For a typical Harmony Type 1 project, the total duration is 28 months. According to the schedule, the planned progress at the end of 10th month is that 18% of the total work should have been completed. Consequently, if there were a 50% delay in schedule actual progress would indicate that only 9% of the total work are completed. This assumption was incorporated into the model and simulation results are shown in Figure 3.

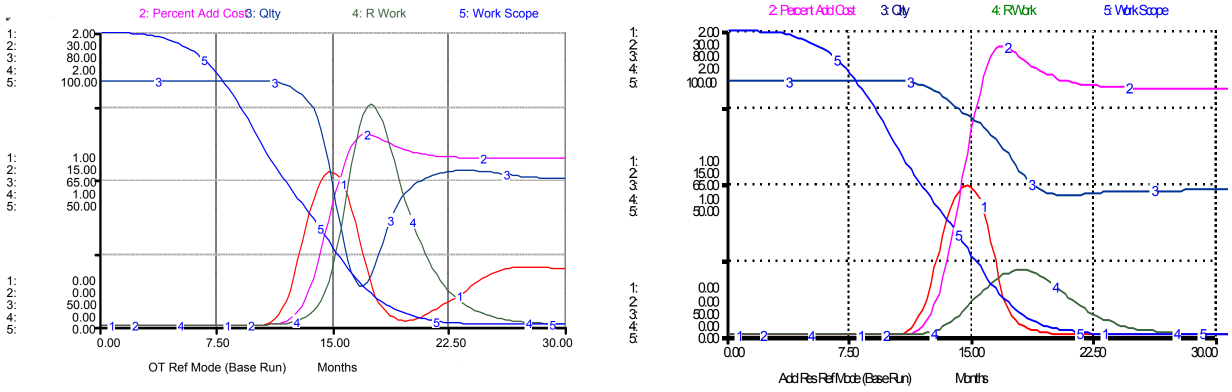


Figure 3. (a) Reference mode for overtime working (b) Referencee mode for resource allocation

Figure 3a shows only the effect of overtime works on project cost, quality and rework, as no additional resources have been prescribed. Similarly Figure 6 indicates only the effect of additional resources on project cost, quality and rework. A comparison of simulation results of Figure 3a and 3b with the respective reference modes in Figure 1 confirms the behavioral validation of the model. Specifically, in Figure 3a, the decline in quality is observed after overtime works are proceeded. Increases in rework are also observed as quality declines. This suggests that a decline in quality is a primary cause of rework. Similarly, simulation results in Figure 3b indicate considerable increase in cost, but a lesser decline in quality and less rework.

GENERATION AND ANALYSIS OF ALTERNATIVE DECISIONS

When a delay occurs in a project, a project manager is often faced with generating and analyzing a number of alternative options before they can make a decision to accelerate schedule. Decision analysis deals with estimation of what will happen if an alternative decision is adopted. In this section, a number of alternative decisions which represent various combinations of prescribing overtime works and injecting additional resources to overcome the identified schedule discrepancy are analyzed. The criteria used for the analysis include additional cost (measured as the percentage of additional cost increase), quality decline and rework generation. The following nine alternatives are analyzed. Each alternative represents a typical combination of overtime-work and additional resources, which can be seen in Table 1.

Using the simulation model, values for additional cost increase, quality decline and rework generation caused by each alternative decision is shown in Table 1. A decision-maker is then required to select the most suitable alternative by applying their value system. Through the application of decision-maker's value system, relative ratings of the alternatives can be evaluated using the utility theory.

Table 1. Outcomes of simulations based analysis

Alternative Decisions*	**Decision Criteria**		
	Additional Cost (% increase)	**Quality Decline (% decline)**	**Rework Generation (% Scope)**
1 *(OT=100%, AR= 0%)*	17.47	28.00	5.01
2 *(OT=100%, AR= 50%)*	26.10	25.33	4.73
3 *(OT= 0%, AR=100%)*	25.00	14.93	1.93
4 *(OT= 50%, AR=100%)*	28.00	16.20	2.43
5 *(OT= 50%, AR= 50%)*	23.50	14.40	2.49
6 *(OT= 50%, AR= 40%)*	22.56	13.99	2.51
7 *(OT= 50%, AR= 30%)*	20.20	13.77	2.50
8 *(OT= 70%, AR= 20%)*	20.28	18.72	3.40
9 *(OT= 30%, AR= 60%)*	22.57	14.01	2.06

OT = Overtime Working, AR = Additional Resources Employed

EVALUATION OF OUTCOMES USING UTILITY THEORY

According to Dozzi *et al.* (1996), the transformation of outcomes as a result of analysis into relative ratings of alternatives through application of decision-maker's value system is designated as evaluation. Evaluation deals with estimation of the relative desirability of what is expected to happen. The application of the utility model for the evaluation of outcomes requires that each criterion used for decision-making be defined and represented by a utility function. The utility functions for all criteria represent preferences or trade-offs between criteria and are measured on a scale so that expected utilities of individual criteria can be combined to form a single expected utility. The methodology used to develop the utility function of each criterion is summarized as follows:

- specify the range of interest for each criterion, upper and lower limits (y_U, y_L);
- identify the neutral point of contribution for each criterion, threshold (y_T) and the most preferred point (y_M);
- define the cardinal utility scale by anchoring relative points; and
- develop the utility functions using either a straight-line or exponential function and solve for the constants of each equation.

The range of interest identifies the upper and lower limits (y_U, y_L) for the options of each criterion and formulates the boundaries for numeric inputs. The threshold point (y_T) of each criterion represents the point of neutral desirability. The most preferred point (y_M) represents the best possible option for the particular criterion. The corporate policy and decision-maker's knowledge and experience about similar problems are usually used to define these points. Values for the threshold points used in this paper are identified in Table 2.

Table 2. Definition of criterion, their range of interest and threshold points

Criterion	**Definition**	**Scale**	y_U	y_T	y_L
Additional Cost	Cost incurred for accelerating the schedule	%	0	20	50
Quality Decline	Negative effect on quality during accelerated schedule	%	0	15	40
Rework Generation	Rework generated as a result of low quality and other factors	%	0	10	25

Fixing the utility values with specific options for each criterion derives the scale for each utility function. These options are referred to as relative points and a minimum of two are required depending on the method used for developing utility values. For two relative points, the threshold point (y_T) and the most preferred point (y_M) are used. The utility of the threshold point is set to zero and the utility of the most preferred point of each criterion is set to one.

$u(y_T)_j = 0$ and $u(y_M)j = 1$

The utility functions are created by using either a straight-line relationship or an exponential relationship. The generalized equations of straight line and exponential utility functions are as follows:

Straight-line equation: $u_j(y_j) = A_j y_j + B_j$ (1)
Exponential equation: $u_j(y_j) = A_j e^{B_j y_j} + C_j$ (2)

where $u_j(y_j)$ = utility of criterion j ; and A_j, B_j, C_j = constants for criterion j.

Based on the real world pattern, the authors have selected an exponential equation for developing utility functions for each criterion. The constants of the exponential equation are solved using two relative points of the criteria for which the utility is known and hit and trial method to fulfil the need of a third equation. Utility functions for each criterion are shown in Figure 4.

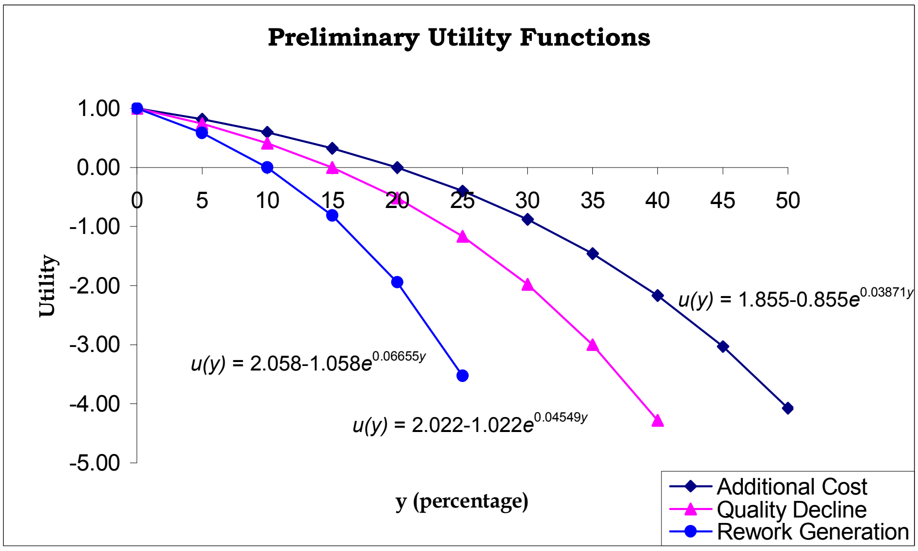


Figure 4. Preliminary utility functions for the selected criterion

The judgement of the decision-maker is required to determine the most preferred number for each criterion $(y_M)_j$. The most preferred number represents the relative contribution of the criterion to the achievement of project objectives. The numbers assigned are scaling factors. The scaling factor for y_j is designated W_j, which is calculated as the multiplication of all the most preferred numbers of other criteria (excluding the most preferred number of criterion j). Using the scaling factor, each preliminary utility function described in Figure 4 can be transformed to an equivalent utility (U_j) value measured on a common scale. The addition of all transformed utilities for all criteria determines the Expected Utility Value *(Eu)* of an alternative decision. An alternative with a higher value of *Eu* represents a better decision. The Expected Utility Values *(Eu)* of all alternative decisions are presented in Table 3.

Table 3. Expected utility calculations for candidate alternatives

		Alternative 1			Alternative 2			Alternative 3		
Criterion	**W_j**	**Outcome**	**u_j**	**U_j**	**Outcome**	**u_j**	**U_j**	**Outcome**	**u_j**	**U_j**
Cost	250	17.47	0.1736	43.40	26.10	-0.4933	-123.32	25.00	-0.3954	-98.85
Quality	200	28.00	-1.6308	-326.16	25.33	-1.2130	-242.60	14.93	0.0064	1.27
Rework	175	5.01	0.5813	101.73	4.73	0.6086	106.50	1.93	0.8550	149.62
Expected Utility				**-181.02**			**-259.42**			**52.05**

		Alternative 4			Alternative 5			Alternative 6		
Criterion	**W_j**	**Outcome**	**u_j**	**U_j**	**Outcome**	**u_j**	**U_j**	**Outcome**	**u_j**	**U_j**
Cost	250	28.00	-0.6725	-168.13	23.50	-0.2684	-67.11	22.56	-0.1926	-48.14
Quality	200	16.20	-0.1135	-22.70	14.40	0.0544	10.88	13.99	0.0907	18.15
Rework	175	2.43	0.8143	142.50	2.49	0.8093	141.63	2.51	0.8077	141.34
Expected Utility				**-48.33**			**85.40**			**111.35**

		Alternative 7			Alternative 8			Alternative 9		
Criterion	**W_j**	**Outcome**	**u_j**	**U_j**	**Outcome**	**u_j**	**U_j**	**Outcome**	**u_j**	**U_j**
Cost	250	20.20	-0.0138	-3.45	20.28	-0.0196	-4.90	22.57	-0.1933	-48.34
Quality	200	13.77	0.1100	21.99	18.72	-0.3729	-74.58	14.01	0.0890	17.80
Rework	175	2.50	0.8085	141.48	3.40	0.7314	127.99	2.06	0.8445	147.79
Expected Utility				**160.03**			**48.51**			**117.25**

According to the expected utility value, Alternative 7 is the ideal solution among the alternatives for mitigating project delays.

CONCLUSIONS

Delays in construction projects are typically managed by expediting progress through prescribing overtime working hours or procuring additional resources or a combination of both. However, although studies have demonstrated the impact of either option on project performance, the interactions between both options and the subsequent impact on project performance has not been previously studied. A system dynamics model called MiDiCON was developed and utility theory applied to examine the effects of various combinations of overtime work and additional resources on project performance. The results from the simulation runs of the system dynamics model showed that the sanctioning of overtime and/or the injection of additional resources may cause declines in quality, which can cause rework. Furthermore, in a utility-based analysis of nine alternative combinations of applying overtime and additional resources, the combination of 50% overtime and 30% additional resources was also rated highest as the most appropriate combination of the two options for mitigating construction project delays.

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