System dynamics approach for construction risk analysis

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Abstract: *Presence of risks and uncertainties inherent in project development and implementation plays significant role in poor project performance. Thus, there is a considerable need to have an effective risk analysis approach in order to assess the impact of different risks on the project objectives. A powerful risk analysis approach may consider dynamic nature of risks throughout the life cycle of the project, as well as accounting for feedback loops affecting the overall risk impacts. This paper presents a new approach to construction risk analysis in which these major influences are considered and quantified explicitly. The proposed methodology is a system dynamics based approach in which different risks may efficiently be modeled, simulated and quantified in terms of time, cost and quality by the use of the implemented object oriented simulation methodology. To evaluate the performance of the proposed methodology it has been employed in a bridge construction project. Due to the space limitations, the modeling and quantification process for one of the identified risks namely "pressure to crash project duration" is explained in detail.*

Keywords: *System Dynamics, Construction Industry, Decision Making, Risk Analysis*

Introduction

Many construction projects do not achieve all their intended goals. Such failure could be realized in terms of severe project delay, cost over runs and poor quality. The presence of risks and uncertainties inherent in project development and implementation plays significant role in such a failure inherent in all stages of project (i.e., planning, bidding, contracting and construction stages). Thus, there is a considerable need to incorporate the risk management concepts into construction practice in order to enhance the performance of the project.

The idea that risk management should be an important and integral part of project management is currently well and widely recognized by the leading project management institutions (PMI 2000[1], IPMA 1998[2]). Different levels of risk management have been proposed by the researchers and organizations during last decade. Al-Bahar and Crandall [3], the U.K. Ministry of Defense [4], Wideman [5], the U.S. Department of Defense, and the U.S. Department of Transportation [6] are among those suggesting the use of a process with four or five phases. These phases mainly include identification, analysis, response planning, and control [7], [8].

In the risk analysis phase, as the most important phase of the risk management process, consequences of different risks on project objectives are assessed. Analysis of consequences may also aid us to identify the most important influencing factors on project performance to take appropriate timely response in facing with them.

Several approaches have been presented in the literature to perform risk analysis phase. However, all of them face one or combination of the following defects:

- Conventional risk analysis approaches do not consider dynamic nature of risks throughout the life cycle of the project, as well as accounting for feedback loops affecting the overall risk impacts. Due to the systemic nature of risks[9] resulting from cause and effect feedback loops, most of the commonly practiced methods have proved inefficient to assess the actual impact of risks as

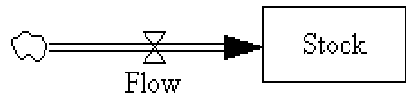

Fig.1 Stock and flow structure

they do not consider such a systemic nature.

- Traditional risk analysis techniques have not the capability to quantify the full impact of different risks, as they do not consider the indirect effects of risks.

- While potential risk events may have major influences on project cost, time and quality, conventional risk analysis techniques can only assess risk consequences based on their impacts either on the project cost or project time.

- Most of the traditional risk management techniques deal with the risk analysis process from a qualitative point of view [10].

This research presents a new risk analysis approach, which explicitly accounts for all the shortcomings associated with the commonly practiced approaches. The proposed methodology is a system dynamics (SD) based approach in which all different risks may efficiently be modeled and simulated by the use of the implemented object oriented simulation methodology. With the proposed methodology all of systemic natures of risks could be considered explicitly.

In the proposed methodology, different risks could be modeled as feedback loops and their impacts on project objectives can be quantified in terms of time, cost and quality efficiently. In comparison to the conventional risk analysis approaches, the SD approach has the capability to quantify the full impact of different risks by considering both direct and indirect effects of each risk through the feedback loop analysis. The proposed SD simulation model provides a powerful tool, by which the impact of various risks on project objectives can be quantified prior to their occurrence by creating a learning laboratory and their full impacts can be considered effectively.

System Dynamics Approach

System dynamics is a methodology for studying and management of dynamically complex systems by building and applying simulation models [11]. System dynamics (SD) was developed in the late 1950s for analysis of industrial systems [12]. SD has been successfully applied to issues, ranging from social, industrial and environmental to project management systems.

System dynamics modeling is useful for managing and simulation of processes with two major characteristics: (1) they involve changes over time and (2) they allow feedback-the transmission and receipt of information [13]. Much of the art of system dynamics modeling is discovering and representing the feedback processes, which along with stock and flow structures, time delays and nonlinearities, determine the dynamics of a system [14]. Stocks and flows are used to model the flow of work and resources through a project [15] (Fig1). Stocks represent stored quantities and characterize the state of the system and generate the information upon which decisions are based. Flows are the rate of increase or decrease in stocks [14]. Information feedback loops are used to model decisions and project management policies [15].
SD modeling can be applied adequately to construction domain problems. The reason is that Construction projects:

- Are extremely complex , consisting of multiple interdependent components
- Are highly dynamic
- Involve multiple feedback processes

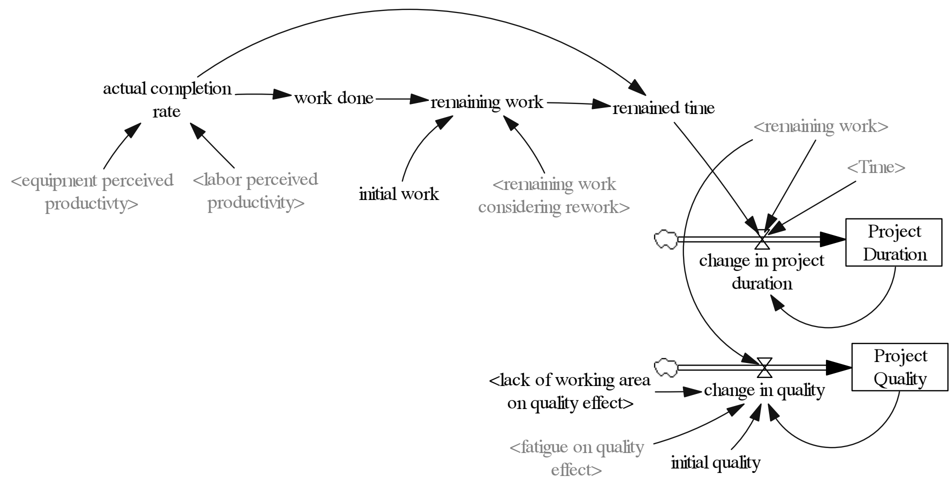

Fig.2 Schedule and quality sector

- Involve nonlinear relationships
- Involve both hard (quantitative) and soft (qualitative) data. [16]

SD is suited to handle these situations more than any other modeling process [15].

Dynamic Risk Analysis

As a preliminary stage and before starting the risk analysis process, the construction project process must be modeled and simulated, acting as a baseline during the risk analysis phase. The deficiency of conventional project management techniques and tools arising from the multiple feedback processes involved in construction projects and also the highly dynamic nature of construction process, has motivated some scholars to seek for a complementary tool. System dynamics approach is a powerful alternative enabling us to account for these characteristics.

Hence, in this research the construction project process simulation model (CPPSM) is built by system dynamics approach. For this purpose, all dynamics and feedback loops involved in a construction project are captured and modeled and qualitative model of the project is built. The proposed model employs the system dynamics modeling approach and borrows its conceptual foundation from the model proposed by Ford and Sterman [11], [17] which was originally developed for product development projects. So, some augments have been made in their original model, to suit it to the construction projects. After preparation of qualitative model of the project, the interrelationships between different variables of the identified feedback loops are assessed by appropriate mathematical functions and the quantitative model of the project is built.

The model structure should successfully capture the complexity of the project management process while being easily comprehendible. Therefore, sub models are used in the CPPSM. The sub models used in this research are called sectors. The CPPSM has the following sectors:

The cost sector, schedule sector, quality sector, resources sector, productivity sector and process structure sector. The developed construction project process simulation model (CPPSM) is extensively large and due to the space limitation, two small sectors of the overall model are presented here. Researchers may contact the senior author for further information. For descriptive purposes, the schedule and quality sector and cost sector of this model has been presented in Figs (2) and (3). As it can be seen in these figures, the schedule, quality and cost sector aid us to determine the project performance measures through the time.

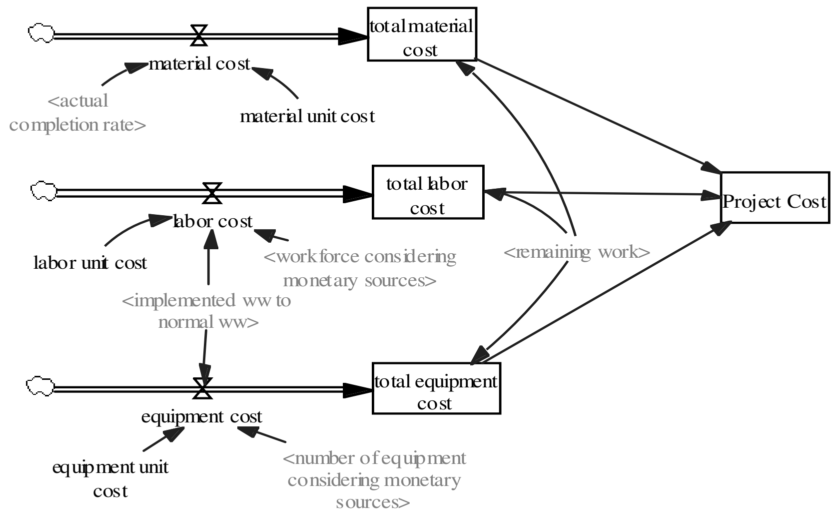

Fig.3 Cost sector

After preparation of the CPPSM, the proposed SD approach methodology is implemented to perform risk analysis (Both qualitative and quantitative).

For this purpose, first the main risks of construction project must be identified. Potential risk events affecting the project can be identified by the use of proposed System Dynamics based approach. These risks can be identified by influence diagrams as events resulting from positive (or self-reinforcing) loops, negative (or self-correcting) loops or some external factors.
In positive loops, the growth of system will be continued due to the positive impacts resulting from the loop and the problem will be exacerbated over the time. But in negative loops the growth will be finally stopped due to the negative impacts resulting from these loops. [14]
After identification of potential risk events as feedback loops, their consequences on project objectives may be analyzed effectively using proposed system dynamics methodology. At the first stage, the impact of each risk event can be analyzed qualitatively. For this purpose the probability and impact of each risk event can be assessed through analyzing different feedback loops affecting each risk event.

At the second stage, the risk events will be analyzed quantitatively. For this purpose, the interrelationships between different variables constitute the feedback loops will be defined by adequate mathematical functions. Then the prepared CPPSM will be simulated for a scenario where the risk occurs. Since the risk event act as a positive loop, negative loop or some external factors on the CPPSM, the model behavior will be changed from the base run, due to the existence of risks. The impact of each risk event on different project objectives can be quantified by the comparison of system behavior resulting from CPPSM with and without risk elements. CPPSM simulates the project outcomes in terms of time, cost and quality. Hence, the impact of each risk on every project performance criteria may be quantified.

The achieved results are more reliable than all other traditional risk analysis approaches as the systemic nature of risks affecting the overall risk impacts is accounted for through the recognized cause and effect feedback loops.
This approach provides a learning laboratory, in which one can simulate the consequences of different risks on project performance before their occurrence in a virtual environment.

Application of proposed Methodology

To evaluate the performance of the proposed methodology, it was employed to quantify the consequences of identified risks in a bridge

Table1 List of identified risks

No	Risk
1	Pressure to crash project duration
2	Inflation
3	Adverse weather conditions
4	Request for contribution to local community
5	Increased payment in replying with changed labor standard law
6	Discrepancy in geology or topographic conditions
7	Change orders
8	Underestimation of construction costs due to lack of information
9	Inefficiency of owners supervisors
10	Material overuse by subcontractor with poor technique or working habits
11	Changed labor safety laws or regulations
12	Schedule delay caused by rejection of unqualified material
13	Construction accidents resulting from operating errors or carelessness
14	Reworking or delay of work due to poor workmanship of subcontractor
15	Machinery breakdown suspending construction activities
16	Faulty design not detected by contractor in tendering process
17	Construction errors due to faulty design but not checked in time by contractor
18	Deficit in Financial Sources
19	Inefficient owners supervisors

construction project. There are 19 risks identified for this project based on the interviews being done be the experts being involved in this project and the other similar projects. These risks have been quantified by the proposed SD approach (Table1). Due to the space limitations, one of the identified risks namely "pressure to crash project duration", has been selected for detail consideration.

Modeling risk of "Pressure to Crash Project Duration" (PCPD)

The pressure to crash project duration is one of the essential risks inherent in construction projects. In this project case example, a transition bridge is being constructed on a lake. This project is part of a bigger mega project which is a highway project across through the lake. Since it has been asked by the client to crash the original duration of highway mega project, it is anticipated that there would be a request from the main contractor to crash the preliminary duration of bridge project to bear some part of the external pressure. This risk may cause major negative impacts on project objectives in terms of cost overrun, project delay and poor quality. In this section the reason for such a failure is investigated by considering and modeling all feedback loops affecting this risk as shown in Fig.4. In the next section, these negative effects are simulated, analyzed and quantified by the use of proposed SD methodology.

Conceptual diagram and associated feedback loops affecting the risk of PCPD is presented In Fig.4. Three alternative actions are introduced to crash project duration in order to fulfill it demanded crashed time.

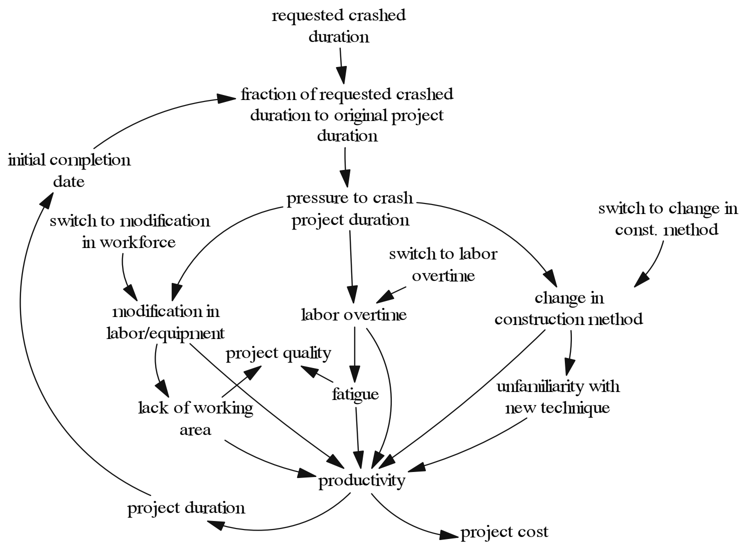

Fig.4 Conceptual model of "pressure to crash project duration" risk

These actions include use of overtime labor policy, modification in labor/equipment policy, or changing construction method. Depending on the trend and habits of parties involved in a project, one or combination of the above actions may be selected in different projects to crash project duration by increasing the project productivity. However, each of these actions has some simultaneous negative side effects on project productivity which may consequently lead to project delay, cost overrun and poor quality. These side effects have also been incorporated into the model by some arcs, which accounts for fatigue, lack of working area and unfamiliarity with new technique respectively.

Overtime Labor Policy

The first possible action which may be implemented to crash project duration is use of overtime labor policy. In this case, the value of workweek increase from 44 hours per week (relative to a normal workweek) based on the impacts of schedule workweek effect. The schedule workweek effect is defined by the fraction of original project duration (time remaining to completion) to requested crashed duration (time available to completion). According to the schedule workweek effect, the required workweek is determined.

However if the workweek hours exceed from 44 hours, it would have negative side effects on productivity and quality due to the labors fatigue. Furthermore, labor fatigue will cause some rework as the fatigue will increase the probability of flaw accordingly. Detailed modeling of over time labor policy to gain required workweek and fatigue impact is presented in Fig.5.

Modification in Labor/Equipment Policy

The second possible action which may be implemented to crash project duration is to modify the number of labor/equipment assigned to the project. The Detailed model of modification in labor/equipment policy is presented in Figs.(6) and(7), which allows determination of the construction labor/equipment required to perform a specific activity in the required duration. As it can be seen, the amount of current labor/equipment is adjusted to the required labors/equipment by hiring new labor/equipment. In this modeling structure, the amount of labor/equipment is increased based on the fraction of original project duration to requested crashed duration. However if the labor/equipment exceeds a case dependent maximum value, it will have negative impacts on productivity and quality due to lack of working area.

Change in Construction Method

The third possible action which may be

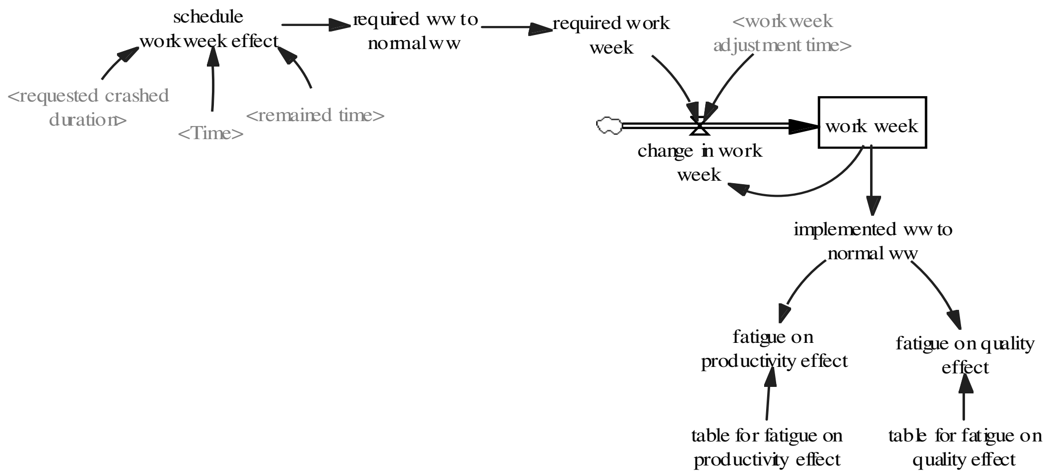

Fig.5 Detailed model of over time labor policy

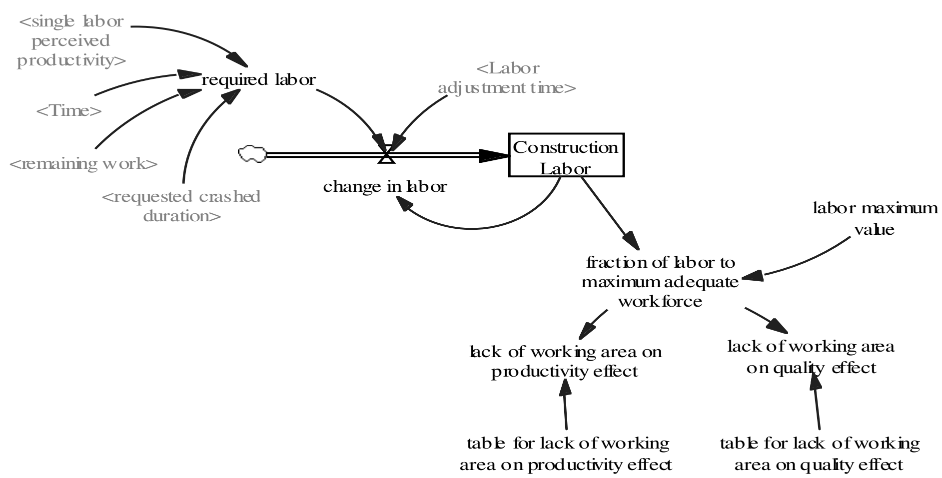

Fig.6 Detailed model of modification in labor policy

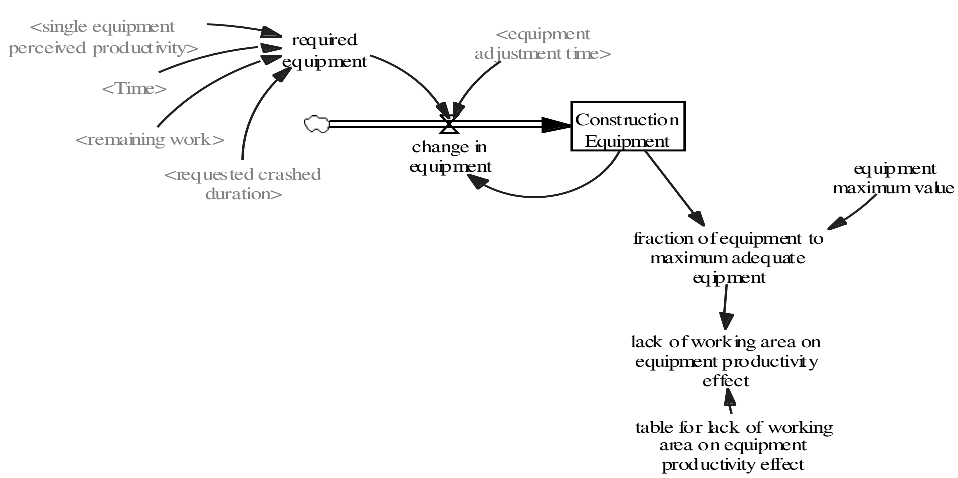

Fig.7 Detailed model of modification in equipment policy

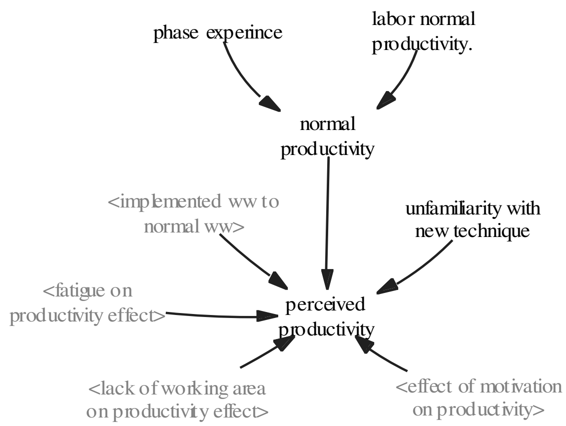

Fig.8 Detailed model of productivity

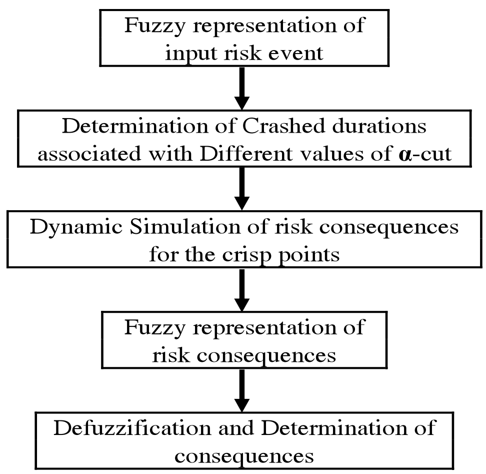

Fig.9 Performed stages for quantification of "PCPD" risk

implemented to crash project duration is to change construction method. However, implementation of this action may have negative side effect on project due to unfamiliarity with new technology. Unfamiliarity with new technique will decrease the perceived productivity accordingly. Detailed modeling of change in construction method effect on productivity is presented in Fig.8.

Analysis of Consequences

With the model in hand, effects of risk of pressure to crash project duration (PCPD) on project objectives, was quantified by the proposed SD approach. For this purpose, the interrelationships between different variables of the identified feedback loops were assessed by appropriate mathematical functions. Details of these functions are available from the authors upon request. In the base case, the preliminary duration of real world project was determined as 10 months. The total cost of the project including both direct and indirect costs was approximated as 7 millions dollars.

The effect of "PCPD" risk on project objectives may now be quantified. The quantification of "PCPD" risk consequences may be performed in five stages as shown in Fig.9.

It is very difficult, if not impossible, to define risk of PCPD, probabilistically. However, depending on it governing conditions and past behavior of the owner, one may assign a linguistic description

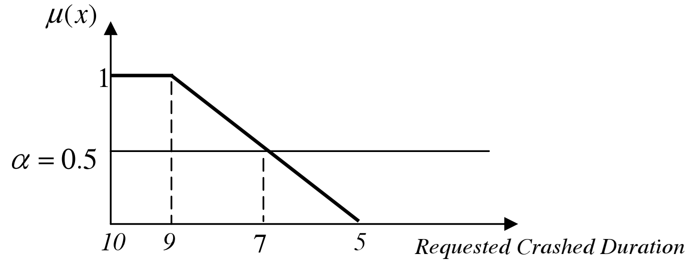

Fig.10 Fuzzy set of requested crashed duration

to PCPD.

Fuzzy Sets (FSs) are designed to deal with a wide range of real-world domains involving linguistic descriptions [19]. The imprecise and uncertain nature of construction projects lends itself to the use of FSs.

By adopting the FS theory, a linguistic variable is converted into mathematical term by a FS. Let S be a fuzzy number; i.e, a normalized convex fuzzy subset as:

$$S = \{(x, \mu_s(x)) \mid x_i \in X\}$$

Where X=range of possible values; and
$\mu_s(x)$ = membership function taking values from [0, 1], specifying to what degree x belongs to the fuzzy set S. A fuzzy number must have a unique model value, be convex, and piecewise continues.

In fuzzy sets theory, an α-cut of a fuzzy set is a set containing members with membership values greater than or equal to a specified $0<\alpha \leqq 1$. In fact, a fuzzy set can be represented through its α-cuts which all are crisp sets. In other words, α-cuts of a fuzzy set, which are fuzzy subsets whose elements membership grades are equal to or greater than $0<\alpha \leqq 1$, can uniquely represent that fuzzy set [20].

The α-cut level set or α-level cut of A is the set:

$$S^{\alpha} = \{(x, \mu_s(x)) \geq \alpha | x \in X\} \quad \forall \alpha \in [0,1]$$

Where S^{α} is an ordinary subset of A.

Based on the α-cut concept, an uncertain variable represented by a fuzzy number can be transformed into crisp sets. α represents the degree of risk that the managers is prepared to accept.

Fuzzy Presentation and Evaluation of Risk Consequences

According to Fig.4, for quantification of the consequences of "PCPD" risk on project objectives, the "requested crashed duration" must be estimated. This is an input to the simulation process, based on which consequences of this risk event on different project objectives will be quantified.

Since there are many uncertainties inherent in the evaluation of probability distribution function of the requested crashed duration at earlier stages of a project, fuzzy set theory has been employed to model these uncertainties.

As explained before, in this project case example, it is anticipated that there would be a request from the client to crash the preliminary duration of bridge project. In Fig.10, the anticipated requested crashed duration is presented by a trapezoidal fuzzy number considering the project governing conditions and past behavior of the owner. According to this figure, the requested crashed duration varies between 5 to 10 months. According to this figure, the most likely crashed duration is between 9 to 10 months which has a membership function of 1 and the least likely crashed duration is anticipated as 5 months which has a membership function of 0. A range of other crashed durations is also possible which receive different membership functions between 0 to1.

To evaluate the consequences of PCPD risk, five

Table2 Simulated consequences of "PCPD" risk for the crisp points

α-cut level	Crisp points of Requested Crashed Duration (Months)	Cost(Dollars)		Quality	
		OTP	MLEP	OTP	MLEP
1	10	7000000	7000000	1	1
1	9	7077630	7019680	0.9948	0.9938
0.75	8	7168610	7045670	0.988	0.9861
0.50	7	7281900	7080960	0.9775	0.9757
0.25	6	7515610	7132680	0.9502	0.9611
0	5	8272890	7349310	0.8023	0.9266
Abbreviation: OTP=Over Time Policy & MLEP=Modification in Labor/Equipment Policy					

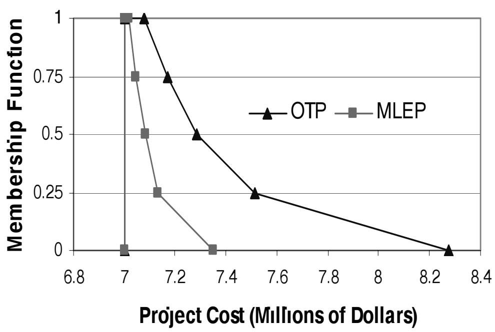

Fig.11 Fuzzy number of "PCPD" risk consequences on project cost

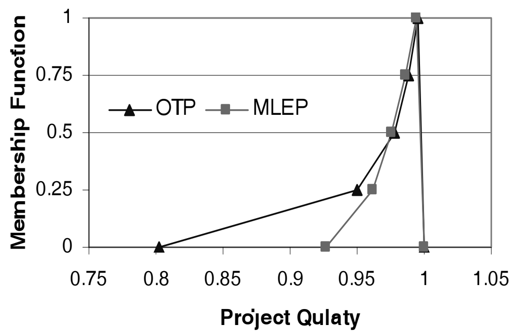

Fig.12 Fuzzy number of "PCPD" risk consequences on project quality

α-cut levels of 1, 0.75, 0.5, 0.25 and 0 were used. The achieved crisp values of crashed project duration were determined as (10, 9), 8, 7, 6 and 5 months respectively.

The crisp values of crashed durations will be given as an input to the proposed system dynamics approach and their consequences on the project objectives are quantified by simulation of system behavior resulting from CPPSM. Solution to the SD simulation model with defined crisp values associated with different α-cuts, yields the overall impact of the risk on the project. Since the crisp inputs to the SD model depend on the selected α-cut, the resulted output is valid for the same value of α-cut. Simulation of consequences for all the crisp points, makes the output of the model as a fuzzy number.

Consequences of the PCPD risk on cost and quality of the project for two different response policies is presented in table 2. The consequences of this risk have been analyzed and compared in the case of implementation of overtime labor policy (OTP) and modification in labor/equipment policy (MLEP). Since change in construction method policy had minor contribution to crash the duration of this project case example, it has been ignored.

Results from OTP and MLEP responses are presented in Figs.11 and 12 as fuzzy numbers for project cost and quality respectively. As it can be seen in Figs.11&12, "PCPD" risk, has resulted in cost overrun and poor quality in the case of implementation of both OTP and MLEP. In this case example, the overtime labor policy (OTP) results in more pronounced increase in cost overrun and/or poor quality compared to modification in labor/equipment policy (MLEP). In the case of OTP, fatigue would have intensive negative impacts on productivity and quality. While in the case of MLEP, these negative side effects due to lack of working area are not pronounced compared to OTP.

The results show that in the case of OTP, the cost overrun would be in the range of 7 to 8.27 millions of dollars. While in the case of MLEP the cost overrun is in the range of 7 to 7.35 millions of dollars. Similarly, in the case of OTP project quality would be varied between0.8 to 1, while in the case of MLEP the project quality is in the range of 0.93 to 1.

Centre of area method, is used for difuzzification of the achieved fuzzy sets. Therefore, the crisp defuzzified value of project cost(C) or project quality (Q) may be approximated as:

$$C(Q)^{*}=\frac{\int C(Q)\mu_S(x)dx}{\int \mu_S(x)dx}$$

Using the proposed defuzzification method for PCPD risk and OTP response policy, project cost and quality changed from base case to 7.38 millions of dollars and 0.95 respectively. Similarly, in the case of PCPD risk and MLEP response policy, the project cost and quality changed to7.10 millions of dollars and 0.97 respectively.

Conclusions and Remarks

In this research a new risk analysis approach was presented which resolved major shortcomings of the commonly practiced risk analysis techniques. The proposed system dynamics (SD) based approach considered dynamic nature of risks throughout the life cycle of the project by dynamic simulation of construction project processes (CPPSM) as well as modeling and simulating the potential risk events. Both direct and indirect effects of risks were considered by implementation of the feedback loop analysis and the full impacts of risks were quantified.

Risk analysis in a bridge construction project was conducted to evaluate the performance of the proposed methodology. It was concluded that it offers a flexible and robust alternative means for risk analysis in the large scale construction projects. One of identified risks namely "Pressure to crash project duration" was selected for detail risk analysis and modeling. Due to the uncertainties inherent in the risk analysis process, fuzzy logic was integrated into the system dynamics based model and consequences of PCPD risk were evaluated. Theses consequences were quantified in terms of cost overrun and poor quality. In the presented case example, the overtime labor policy (OTP) resulted in more pronounced increase in cost overrun and poor quality compared to modification in labor/equipment policy (MLEP) due to its more pronounced negative side effects.

Finally, it was concluded that the proposed SD risk analysis approach provides a powerful tool, by which the full impact of various risks on every project performance criteria including time, cost and quality can be quantified efficiently prior to their occurrence by creating a learning laboratory in a virtual environment.

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