A Risk-based Critical Path Scheduling Method (Ⅰ) : Model and Prototype Application System

H.K. Chang[a] W.D. Yu[b]* and S.T. Cheng[c]

[a]Department of Civil Engineering, Chung Hua University, Taiwan
[b*]Department of Construction Engineering, Chaoyang University of Technology, Taiwan, Corresponding Author
[c]Department of Construction Management, Chung Hua University, Taiwan
E-mail: d10304006@chu.edu.tw, wenderyu@cyut.edu.tw, shaotsai@chu.edu.tw

Abstract

The traditional cost-based Earned Value Management (EVM) method, and the related Earned Schedule Management (ESM) and Earned Duration Management (EDM), for construction project schedule control has been founded on the basis of Planned Value (PV). However, the relevant risk factors are usually not taken into account while the scheduler is estimating the duration of an activity. As a result, *de facto* value of PV is far away from the original planned one when the risk scenarios occur to the activities. To tackle the abovementioned problem, the current research proposes a Risk-based Critical Path Scheduling Method (R-CPSM) that assist the scheduler to take into account the spatial and various resource constraints as well as the environmental influences when he/she is planning the schedule of a project. A computer program to implement the proposed R-CPSM, namely Risk-based Critical Path Scheduling System (R-CPSS), is developed to test the feasibility of R-CPSM. The proposed R-CPSS is proved to be able to improve the problems of the traditional EVM schedule control methods due to the inaccurate estimation of the PV.

Keywords: Risk management, EVM, Construction Planning, Schedule Control.

1 Introduction

The cost-based Earned Value Management (EVM) has been the most prevailing tool adopted for construction schedule control. Deriving from EVM, the Earned Schedule Management (ESM) replaces the original cost-based Schedule Performance Index (SPI_c) with the time-based Schedule Performance Index (SPI_t) [1][2][3][4]. On the other hand, Earned Duration Management (EDM), which uses activity duration for evaluation, replaced SPI_c with Duration Performance Index (DPI_t) [6]. Despite the differences, the evaluation of schedule performance for EVM, ESM or EDM are all based on Planned Value (PV), which is determined by the estimated schedule (*i.e.*, Planned Value, PV. As a result, the accuracy of the performance evaluation usually depends on the accuracy of PV. However, when it comes to estimation, engineers usually ignore the influences of various risk factors that acts on the individual project schedule, and the their impacts on the project critical and uncritical paths. Therefore, when the environmental and resource risk factors divert, the estimated PV would be apart from *de facto* value, and eventually leads to the failure of project control, in spite of which method adopted (*i.e.*, EVM, ESM or EDM).

The Precedence Diagramming Method (PDM) based on traditional Critical Path Method (CPM) is the prevailing scheduling method currently adopted in the construction industry. Traditional CPM scheduling usually considers the duration of a construction activity as a fixed value. The Program Evaluation and Review Techniques (PERT) adopting probabilistic durations are not popular due to its complicated theoretical backgrounds and the lack of available computer software. It is desired to develop a scheduling method taking into account the risk factors of activity duration, so that the accuracy and efficiency of traditional project control method can be improved.

As mentioned above, this study aims to propose a Risk-based Critical Path Scheduling Method (R-CPSM) and the implementation system, namely Risk-based Critical Path Scheduling System (R-CPSS). The objectives are to improve the accuracy of PV estimation and the usefulness of the risk-based scheduling method.

2 Review of Related Works

The relevant literature reviewed in this section include: (1) various scheduling techniques; and (2) the integration of risk management and scheduling.

2.1 Various Scheduling Techniques

Previous important developments of traditional scheduling techniques include: Gantt Chart in 1910, CPM and PERT in 1958, Linear Scheduling Method in 1980, and the Repetitive Scheduling Method (RSM) after 1990. The review of these methods can be referred to [7][8]. In the following, these techniques are briefly reviewed:

- Bar Chart

Proposed by Henry Gantt in 1917, therefore also known as Gantt Chart. The original Bar Chart is not capable of schedule analysis because it does not show the relationship between activities. To fix this problem, current commercial scheduling software have combined Bar Chart with CPM to allow Arrow Diagramming Method (ADM) calculation, namely the Enhanced Bar Chart.

- Critical Path Method (CPM)

Differed by network diagrams, CPM can be categorized into Arrow Diagramming Method (ADM), and Precedence Diagramming Method (PDM), Activity on Node (AON). CPM was proposed by Dupont Inc. in 1958. The process of CPM calculation includes Forward Pass, Backward Pass, Float Computation, etc. Activities with zero Total Float connect the longest path, which is called Critical Path (CP) on the network and is the focus for schedule control.

- Program Evaluation and Review Technique

PERT was developed by the Polaris Missile Project of US Special Project Agency in 1957. Considering the Uncertainty of operation conditions and the probabilistic duration of activities, PERT's schedule includes three different time estimations—Optimistic, Most likely, and Pessimistic. With network diagramming technique and probability calculation, PERT is capable of estimating the possible duration and probability of a single activity or the whole project. Besides, it is the first computerized scheduling and controlling method.

- Linear Scheduling Method

Proposed by Johnston in 1981 [8], The Linear Schedule Method uses a line to represent the efficiency of a construction activity. The slope of Linear Scheduling Method diagram is the acquirable workload of a specific activity per unit time, namely the speed of specific activity. Activities can be categorized, by their nature, into Linear Activity, Bar Activity, and Block Activity. The aim of Linear Scheduling Method is to improve the efficiency of the traditional CPM while dealing with repetitive activities.

- Linear Scheduling Model (LSM):

Originated form Harmelink's effort [11] to improve the Linear Scheduling Method in 1995, the Linear Scheduling Model (LSM) categorizes activities by distinguishing their nature with geometrical graphics. In 1998, by analysing the logic relationship between activities, Harmelink built a theoretical similar to the controlling activity path of CPM, which better reflects to the actual condition of the construction work on site than the previous repetitive scheduling techniques. After 2001, Harmelink and other researchers [10][11][12] proposed the float time calculation method for LSM, so they make the theoretical framework of LSM more complete.

- Repetitive Scheduling Method (RSM)

In 1998, Harris and Ioannou developed the Repetitive Scheduling Method (RSM) [13][14][15] by considering the characteristics of repetitive scheduling including the resource continuity of activities, and the convergence, divergence, and parallel of activities relationships. Their method takes the horizontal axis as time and the vertical axis as production. The activities are represented as linear lines. With a simplified graph, RSM is able to represent the relationships between activities and the continuity of resources. It then indicates the performance of the critical path based on logic relationships among the activities.

- Critical Path Segments Scheduling Technique

The Critical Path Segments Scheduling Technique was proposed by Hegazy *et al*. [16]. It aims at resolving the problem of traditional critical path scheduling by taking continuous time as a whole segment. It divides the activities into different time segments to avoid over-complicated networks and is able to identify the impact of critical path on the project schedule more accurately. Therefore, it helps project managers distribute resources more effectively during scheduling.

- Enhanced Arrow Diagramming Method (EADM)

Enhanced Arrow Diagramming Method (EADM) is a new form of scheduling method proposed by Chang [7]. It shows the time scale, construction location, activity sequential logics and activity duration at the same time, and it is capable of improving traditional Arrow Diagram Method [17].

Among the abovementioned scheduling methods, EADM is more suitable to provide the required functions of the Risk-based Critical Path Scheduling Method in the current research. As a result, this study adopts CPM and EADM as the theoretical backgrounds for the proposed Risk-based Critical Path Scheduling Method.

2.2 The Integration of Risk Management and Scheduling

Risk is the probability of events that may cause negative impacts on the objectives. Since the essential nature of a risk is uncertainty, the primary objective of risk analysis is to evaluate whether we should undertake or avoid such risks [18]. There are three major features of risk: (1) Probability—risk is an objective existence, although can be reduced, it cannot be completely eliminated; (2) Uncertainty—if we focus on individual event, whether, how and what it might impact the result is random, which makes it hard to predict with a single event; (3) Predictability—even though single risk event happens randomly, a collection of risk events may occurs complying with a probability distribution, which makes the occurrence of the risk events predictable.

There are three characteristics of a risk event: (1) Uncertainty—whether or how the event might cause the project must be uncertain; (2) Futurity—risk event must be something hasn't happened yet, those already happened can be seen as loss or gain; and (3) Possibility of loss or gain—a risk event must bring a loss or gain as a result to the project. The risk category can categorize risks by their causes or characteristics, thus it help fulfil the needs of risk management. The structure of the category usually contains a major category that can be furtherly derived into layers of subcategories by the nature of risk events. Finally, it will form a Risk breakdown structure (BRS) [18].

In order to better tackle the risk in a construction activity, Yi and Langford [24] proposed an equation to express all risks involved in a construction activity as bellow:

$$\text{Total Risk} = P \times H \times T \times E \qquad (1)$$

where, P means "Process Risk"; H means "Human Risk"; T means "Technology Risk", E means "Physical Environment Risk"; and the symbol "×" implies that the impacts of the risk factors to the schedule is a product of the impacts caused by the individual risk factors.

Yi and Langford believed that the first three risk factors of a construction activity (*i.e.*, process, human, and resource) are determined by the type of the construction activity. They can be broken down by referring to the Bill of Quantity (BOQ) of the activity. The fourth risk factor, Physical Environment Risk, is determined by the location and surrounding conditions of the work site. Such a risk breakdown concept is very useful for analysis of the risk factors affecting construction schedule. However, no systematic approach was proposed by Yi and Langford to take the above-mentioned factors in construction scheduling process. In this paper, we develop a systematic risk-based critical path scheduling method (namely, R-CPSM) to take into account all risk factors referred by Yi and Langford [24].

Other literature related to the integration between risk management and scheduling includes: (1) Application of risk analysis to float utilization and optimization [20][21]; (2) Application of risk evaluation to scheduling optimization [22][23]; (3) Risk-based scheduling and safety programming [24]; (4) Algorithm of risk reduction [25]; (5) Integration of risk management and scheduling technique [26]; (6) Case study of risk-based scheduling application [27]; (7) Quantitative method for risk analysis [28][29]; (8) Integration of schedule control and risk information [30]. From the above literature, it is found that the integration of risk management with scheduling techniques can be beneficial to project management.

3 Risk-based Critical Path Scheduling Model (R-CPSM)

In this paper, a Risk-based Critical Path Scheduling Model (namely R-CPSM) is proposed. This section is dedicated to the model development of R-CPM.

3.1 The Seven Risk Levels of Construction Activity Duration

Inspired by the safety planning method proposed by Yi and Langford [24], the duration of a construction activity can be affected by the integration of the individual risk factors on that activity. It is believed that the spatial restriction of the construction site is the essential constraint for the duration to complete an activity. As a result, the estimated duration for a construction activity considering the spatial constraint is called "base duration". The base duration can be deemed as the shortest possible duration required to complete the activity without occurrence of any risk event.

The second constraint for the duration of completing an activity is the "physical environment risk". The physical environment risk considering all factors of the surrounding environment on the construction site, *e.g.*, weather, local social factors, and local cultural factors. The impact of such factors to the activity duration is usually difficult to estimate and is usually measured by experienced engineers who are familiar with the surrounding environment factors. As a result, while take the physical environment risk into account, the modified activity duration is called "empirical duration". The estimation of the empirical duration can be obtained by adding an extra duration to the base duration, and thus it is longer than base duration.

Beside the physical environment risk, which is inevitable, there are five categories (*i.e.*, the 5 Ms of construction management) of resource risks that can be altered by management schemes including: (1) Man—the availability of different skilled or unskilled laborers to perform a construction activity; (2) Machine—the availability of required equipment to perform a construction activity; (3) Material—the availability of required materials to complete a construction activity; (4) Method—the availability of appropriate construction methods to perform a construction activity; and (5) Money—availability of required financial arrangements to conduct a construction activity. Should any of the above resources be absent, the completion of a construction activity will be delayed and the duration will be lengthened.

Considering all the above risk factors, seven risk levels are classified for estimating the duration of a construction activity:

- Level-0 duration—no risk event occurs and the physical environment risk contributes no extra duration to the activity, this is also considered as the base and shortest duration of a activity. The Level-0 duration is denoted as RD_0 and calculate by the following equation:

$$RD_0 = \frac{\text{Quantity}}{\text{Rate}} \tag{2}$$

Where, "Quantity" is the quantity of product to be produced by the activity; "Rate" is the productivity rate that can be referred to any cost estimation reference, *e.g.*, RSMeans Book (https://www.rsmeans.com) or Dodge Estimating Guide (https://construction.com)；RD_0 is the "base duration" of a construction activity.

- Level-1 duration—only the physical environment risk but no any other resource risk occurs, so the extra duration caused by the physical environment risk estimated by the experienced engineer is added to the base duration resulting in the "empirical duration". The Level-1 duration is denoted as RD_1 and calculate by the following equation:

$$RD_1 = RD_0 + (\text{Environment Effect}) \tag{3}$$

Where, RD_0 is "base duration of the activity; "Environment Effect" is the extra duration caused by the physical environment risk and is estimated by the experienced engineer. RD_1 is the "empirical duration".

- Level-2 duration—both the physical environment risk and one resource risk occur, so the extra duration caused by the occurred resource risk estimated by the experienced engineer is added to empirical duration, resulting in Level-2 duration.
- Level-3 duration—not only the physical environment risk but also two of the five resource risks occur, so the extra durations caused by the two occurred resource risks estimated by the experienced engineer are added to empirical duration, resulting in Level-3 duration;
- Level-4 duration—not only the physical environment risk but also three of the five resource risks occur, so the extra durations caused by the three occurred resource risks estimated by the experienced engineer are added to empirical duration, resulting in Level-4 duration;
- Level-5 duration—not only the physical environment risk but also four of the five resource risks occur, so the extra durations caused by the four occurred resource risks estimated by the experienced engineer are added to empirical duration, resulting in Level-5 duration;
- Level-6 duration—not only the physical environment risk but also all five resource risks occur, so the extra durations caused by the five occurred resource risks estimated by the experienced engineer are added to empirical duration resulting in Level-6 duration, and this is considered the worst case scenario of the activity duration.

The equation for estimating the activity duration for Risk Level-2~ 6 is described in the following:

At first, the most significant resource risk factor for each of the five resource types is identified as M_x using the following equation:

$$M_x = \text{Max}\ (M_{x1}, M_{x2}, M_{x3}, M_{x4} \ldots\ldots, M_{xn}) \tag{4}$$

Where, M_x represents the most significant resource risk factor in a specific resource type (*e.g.*, M_1 means the most significant risk factor for human resources, M_2 means the most significant risk factor for machine resources, and so forth.); M_{x1}, M_{x2}, ...M_{xn} are the possible resource factors for a specific resource type (*e.g.*, M_{23} means the third type of machine resource.).

Equation (4) identify the most significant risk factor for each of the five resource types. The dominating resource type from Risk Level-2~6 are determined according to their contribution to the activity duration, and is calculated by the following equation:

$$R\ \{R_2, R_3, R_4, R_5, R_6\} = \text{Sort}\ (M_1, M_2, M_3, M_4, M_5) \tag{5}$$

Where, M_x represents the most significant resource risk factor for each of the five resource types; R_2 is the risk of duration for the Level-2 Risk; R_3 is the risk of duration for the Level-3 Risk; and so forth; "Sort(...)" is sorting function (using descending ordering).

Combining Equation (2)~(5), the activity duration for Risk Level-2~Level-6 can be calculated using the following equation:

$$RD_x = RD_{x-1} + R_x \quad (6)$$

Where, RD_x is the activity duration for Risk Level-x (e.g., RD_2 is the activity duration for Risk Level-2), *s.t.* $2 \leq x \leq 6$; the "Round Law" is adopted in calculating RD_x in order to obtain the most conservative estimate of risk duration for the activity.

It is noted that there may be more risk factors affecting the construction activity duration in different types of construction works. The R-CPSM can be expanded by including more risk categories. However, the five resource categories plus the physical environment risk are common for almost all types of construction works; therefore the preliminary R-CPSM consider only the above-mentioned seven risk levels for activity duration estimation. Table 1 shows the associated risk parameters with the seven risk levels for the duration of a construction activity.

Table 1 Risk parameters for the 7 risk levels

Risk Level	Risk parameter	Note
0	Spatial	Shortest duration
1	Spatial + Environmental	Empirical duration
2	Spatial + Environmental + Single resource	Only 1 resource risk occurs
3	Spatial + Environmental + 2 resources	2 resource risks occur
4	Spatial + Environmental + 3 resources	3 resource risks occur
5	Environmental + 4 resources	4 resource risks occur
6	Environmental + 5 resources	All 5 resource risks occur

3.2 Development of the Risk-based Critical-Path Scheduling System (R-CPSS)

The Risk-based Critical-Path Scheduling System (R-CPSS) is developed to implement R-CPSM. The R-CPSS scheduling process is depicted in Figure 1, which includes: (1) Project Creation—create the basic information of the project; (2) Location Definition—define the space information of the construction site; (3) Activity Definition—create the activity list and estimate the activity durations; (4) Relationship Connection—set up the sequential relationships among activities under the limitations of location and resources; (5) Risk Item Breakdown—breakdown the risk events and estimate their influences on the activities with aids of the risk database; (6) Risk Allocation—allocate risk items to the activities; (7) Information check—before the duration calculation, check the accuracy of location information, relationships, and risk information; (8) Risk Duration Calculation—apply the 7-risk-level method to calculate the duration of each activity; (9) CPM Calculation—apply the R-CPSM to calculate the overall project duration and critical path for the seven risk levels; (10) Diagram Drawing—draw a proper diagram (PDM, EADM or Bar Chart) based the R-CPSM calculation results.

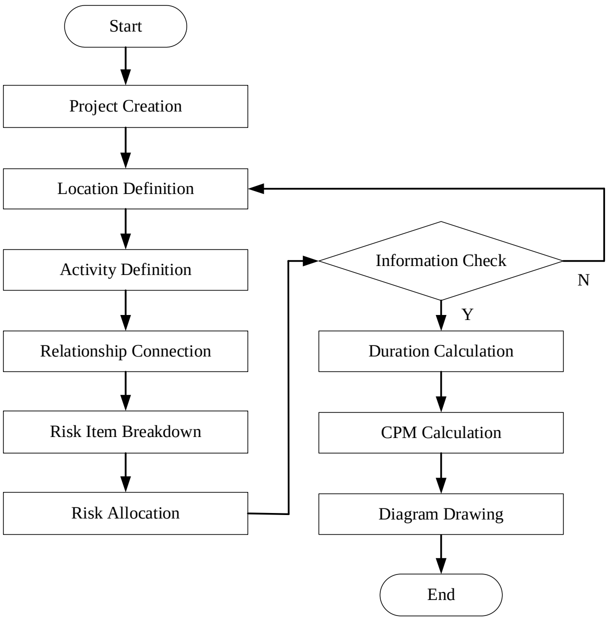

Figure 2 Operation procedure of R-CPSS

4 Application of Risk-Based Critical-Path Scheduling System

In this section, a road construction project is used to demonstrate the functionality of the proposed Risk-based Critical Path Scheduling System (R-CPSS).

4.1 Demonstration Application of R-CPSS

The demonstration case is a small road improvement project. The site plan of the project is depicted in Figure 3. The works of the project include: mobilization (F-01), left-wing sewer (L-01) and sidewalk (L-02), the demolition (R-01) and construction of right-wing sewer work (R-02), the concrete paving (C-01) and restoration (F-02). The quantity, efficiency and environmental impact on the duration of relative constructions are shown in Table 2. There are four major blocks on the construction site: the preparation area, the right-wing, the left-wing, and the central. Due to the spatial constraints of working space, the right-wing drainage facility can only begin after the left-wing is finished. Considering the spatial limitation, two more days are required to wait for the left-wing to be finished. The demolition of the right-wing facility is arranged right after the project mobilization; the left-wing sidewalk begins after the left-wing drainage is finished; the right-wing drainage is started after the demolition and the left-wing facility drainage is finished. The pavement must wait until the left-wing sidewalk and right-wing drainage are finished. Finally, site restoration comes up after the road is paved. The relationships of above-mentioned activities are shown as Table 3.

The risk analysis of this project reveals that: mobilization and road restoration non-resource risk activities; the drainage works confront man, material and machine risks; demolition activities quote machine and method risks; sidewalks quote man, material and method risks; paving quotes man and material risks. The risk events and their impacts on activity durations are shown in Table 3; the calculated durations of the 7 risk levels are shown in Figure 3; the R-CPSS diagram of the example project is shown as Figure 4.

With the diagram of Figure 4, we can visualize the activities swapping between critical-path and noncritical-path under different risk levels. For instance, the left-wing drainage was critical-path in the empirical duration; however, since that the risk impacts on right-wing demolition work made the critical-path swap to the former one (See Figure 5 and Figure 6).

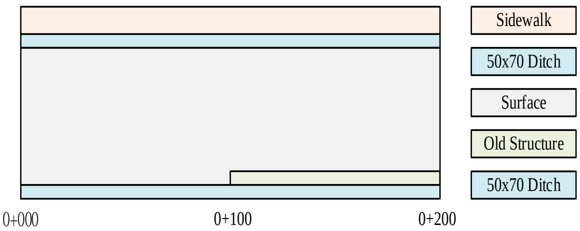

Figure 2 Site layout of the project

Table 2 Activity list of demonstration project

ID	Activity	Q	Rate	Base Dur.	Envir. Impact	Emp. Dur.
F-01	Mobilize.	1.0	-	4.0	1.0	5.0
L-01	Left-Wing Sewer	200.0	40.0	5.0	1.0	6.0
L-02	Left-Wing Sidewalk	200.0	50.0	4.0	1.0	5.0
R-01	Right-Wing Demoli.	100.0	20.0	5.0	1.0	6.0
R-02	Right-Wing Sewer	200.0	40.0	5.0	1.0	6.0
C-01	Paving	1600.0	800	2.0	1.0	3.0
F-02	Restore	1.0	-	3.0	-	3.0

Table 3 Relationships information of demonstration

ID	Precedence Activity	Relationship	Lag
F-01	-		
L-01	F-01	FS	2
L-02	L-01	FS	0
R-01	F-01	FS	0
R-02	R-01	FS	0
	L-01	FS	0
C-01	L-02	FS	0
	R-02	FS	0
F-02	C-01	FS	0

Table 4 Risk information of the demonstration project

ID	Man		Machine		Material		Method		Money	
	R*	D*	R	D	R	D	R	D	R	D
F-01										
L-01	20	1	20	1	20	1				
L-02	10	1	20	1	20	2	50	1		
R-01			20	1			40	2		
R-02	20	1	20	1	20	1				
C-01	10	1			20	1				
F-02										

*Note: R =Probability of risk occurrence (%), D = Lag (Day).

AID	ACode	AName	LevelA	LevelB	LevelC	LevelD	LevelE	LevelF	LevelG
100	F-01	Mobilization	4	5	5	5	5	5	5
200	L-01	Left 50x70 Ditch	5	6	7	8	9	9	9
300	L-02	Left Sidewalk	4	5	7	9	10	10	10
400	R-01	Old Ditch Broken	5	6	10	12	12	12	12
500	R-02	Right 50x70 Ditch	5	6	7	8	9	9	9
600	C-01	Surface Concrete	2	3	3	3	3	3	3
700	F-02	Demobilization	3	3	3	3	3	3	3

Figure 3 Duration of the 7 risk levels

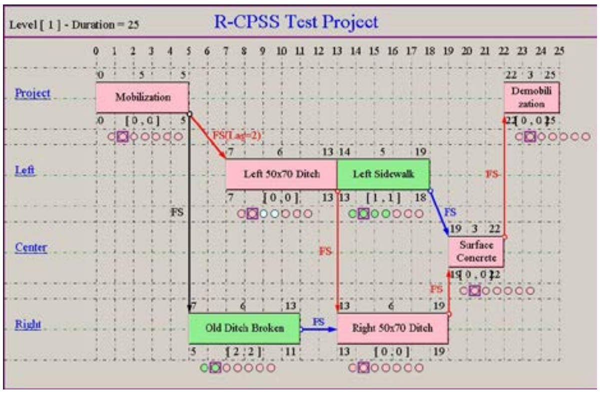

Figure 4 R-CPSS diagram of demonstration project

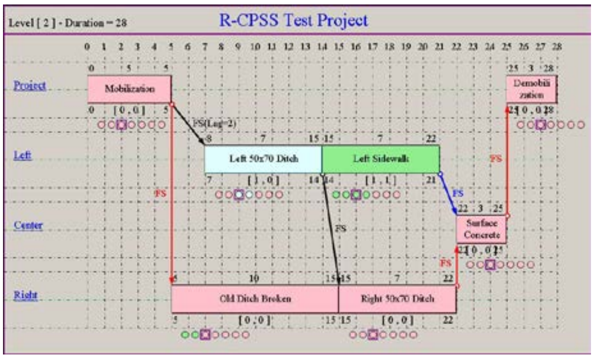

Figure 5 Example of critical path swapping in the demonstration project

(a) Duration change of the left-wing sewer

(b) Duration change of the right-wing demolition

Figure 6 The duration changes and critical path swapping in the demonstration project

4.2 Discussions of the Demonstration

Traditional EVM assumes PV curve as the schedule baseline, and evaluates the project schedule performance by comparing the values of EV with PV using SPI as the indicator. It is found from the demonstration project that the comparison between PV and EV is not meaningful when the impacts of duration risks were not taken into account. As a result, the construction schedule control based on SPI usually fails to detect the project schedule problems correctly. The proposed R-CPSS provides 7 PV-curves for different risk levels. Employing the EV information of the contract price and these 7 PV-curves (PV0~PV6), totally eight ranges on the diagram are identified. Construction managers can adjust the schedule by analysing which range the EV falls, and plan the control actions according to Table 5. The 7 PV-curves of this project are shown in Figure 7. Since this is a small project, the EV value of the finished activities can be estimated using contract payment value. Table 6 depicts the comparison between EV and the 7 PV-curves in the first ten days of the project: on the second and fourth day, the EV are equal to PV1, which implies that the project went well since it only confronted single risk; on the sixth day, the EV fell into area 4, which implies risk events occurred and the schedule didn't go well, the manager should take control action; between the eighth to tenth day, EV was still in area 4, but it's moving to area 5, which indicates that the risk kept rising and the manager should find out the source of risks.

Table 5 Suggested actions for the 7 risk scenarios

No.	Range	Status	Suggested Action
1	$EV<PV_0$	Good	No
2	$PV_0 \le EV<PV_1$	Good	No
3	$PV_1 \le EV<PV_2$	Good	Monitor
4	$PV_2 \le EV<PV_3$	Medium	Control
5	$PV_3 \le EV<PV_4$	Medium	Contingency
6	$PV_4 \le EV<PV_5$	Poor	Fall back
7	$PV_5 \le EV<PV_6$	Poor	Work around
8	$PV_6 \le EV$	Out of control	Re-plan

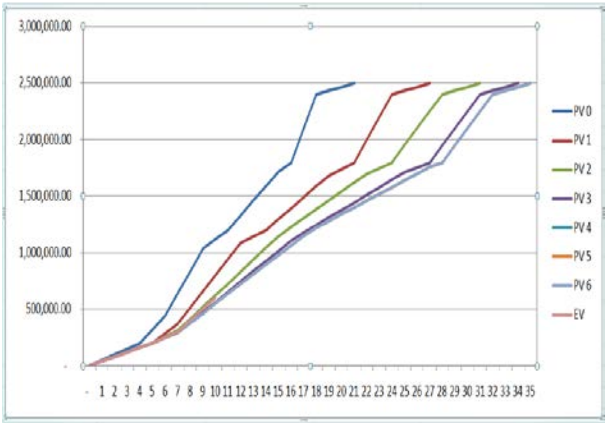

Figure7 The 7 PV-curves of the demonstration project

Table 6 Comparison between EV and 7-risk levels

Time	2	4	6	8	10
PV 0	100,000	200,000	440,000	840,000	1,120,000
PV 1	80,000	160,000	285,714	514,286	800,000

PV 2	80,000	160,000	254,545	413,637	622,727
PV 3	80,000	160,000	246,154	382,906	564,103
PV 4	80,000	160,000	246,154	378,466	550,769
PV 5	80,000	160,000	246,154	378,466	550,769
PV 6	80,000	160,000	246,154	378,466	550,769
EV	80,000	160,000	250,000	400,000	600,000
Com.	PV1 = EV	PV1 = EV	PV2 ≤ EV < PV3	PV2 ≤ EV < PV	PV2 ≤ EV < PV
Risk	3.00	3.00	4.46	4.56	4.61

5 Conclusions and Recommendations

5.1 Conclusions

Traditional critical-path method estimates activity duration by dividing the product quantity with the productivity rate. The proposed R-CPSM suggests to use 7 risk levels to estimate the activity risks and their impacts on the activity duration, then use the 7 PV-curves (PV0~6) to identify current status of the project schedule. The R-CPSM provides the project manager signals of potential risks by indicating which risk range the EV falls, and assists the managers control the schedule more effectively.

5.2 Recommendations

Some directions for future research are listed below:

- The Base Duration in this study was estimated with the traditional manual approach. However, since that the application of Building Information Model (BIM) has become more general, a more accurate Base Duration can be automatically estimated using the quantity information provided by BIM.

The risk items in this study are surveyed according to the personnel's experience. It is suggested to build and integrate a risk item database with BIM to generate risk items and estimate the activity risks automatically.

6 ACKNOWLEDGEMENT

The research was partially funded by the Ministry of Science and Technology, Taiwan, under project No. MOST 104-2221-E-216-014. Sincere appreciations are given to the sponsor by the authors.

References

[1] Walt Lipke, "Schedule is different", *The Measurable News Summer*, 1: 31–34, 2003.

[2] Walt Lipke, Ofer Zwikael, Kym Henderson, Frank Anbari, "Prediction of project outcome: The application of statistical methods to earned value and earned schedule performance indexes." International Journal of Project, 27(4): 400-407, 2009.

[3] Walt Lipke, "Schedule adherence and rework.", *PM World Today*, 13: 1–14, 2011.

[4] Elshaer, R. "Impact of sensitivity information on the prediction of project's duration using earned schedule method." *International Journal of Project Management*, 34(4): 579-588, 2013.

[5] Jacob, D., Kane, M., "Forecasting schedule completion using earned value metrics? Revisited." *The Measurable News Summer*, 1: 11–17., 2004

[6] Khamooshi, H., Golafshani, H., "EDM: Earned Duration, a new approach to schedule performance and measurement." *International Journal of Project Management*, Volume 32, Issue 6, pp. 1019-1041., 2014.

[7] Chang, Hsien-Kuan," Integrated of traditional scheduling techniques - Enhanced Arrow Diagram Method." *Master Thesis*, Department of Construction Management, Chung Hua University, 2014.

[8] Chang, Cing-Jung, "Research of the practical applicability of different construction scheduling (1&2)", Modern Construction, Volume 380, pp.55-64, Volume 381, pp.53-61, 2011

[9] Duffy, G., Oberlender, G., and Seok Jeong, D. "Linear Scheduling Model with Varying Production Rates." J. Constr. Eng. Manage., ASCE, Vol. 137, NO. 8, pp. 574-582, 2011.

[10] Yamin, R. and Harmelink, D."Comparison of Linear Scheduling Model (LSM) and Critical Path Method (CPM)." J. Constr. Eng. Manage., ASCE, 127(5), 374–381, 2001.

[11] Harmelink, D."Linear Scheduling Model: Float Characteristics." J. Constr. Eng. Manage., ASCE, Vol. 127, NO. 4, pp. 255-260, 2001.

[12] Harmelink, D. and Rowings, J. "Linear Scheduling Model: Development of Controlling Activity Path." J. Constr. Eng. Manage., ASCE, Vol. 124, NO. 4, pp. 263-268, 1998.

[13] Harris, R. B., and Ioannou, P. E., "Scheduling Project with Repeating Activity," J. Constr. Eng. Manage., ASCE, Vol. 124, NO.4, pp. 269-278, 1998.

[14] Zhang, L., Pan, C. and Zou, X."Criticality Comparison between the Repetitive Scheduling Method and the Network Model. ." J. Constr. Eng.

Manage. , ASCE, Vol. 139, NO. 10,2013.

[15] Zhang, L. and Qi, J.,"Controlling Path and Controlling Segment Analysis in Repetitive Scheduling Method." J. Constr. Eng. Manage., ASCE, Vol. 138, NO. 11, pp. 1341-1345, 2012.

[16] Hegazy, T. and Menesi, W. "Critical Path Segments Scheduling Technique." *Journal of Construction Engineering and Management*, ASCE, 136(10): 1078–1085, 2010.

[17] Chang, H.-K. and Chang, C.-J., "Research of the application of critical-path method to repetitive project scheduling: the Enhanced Arrow Diagram." *Modern Construction*, 407: 34-45, 2013. (in Chinese)

[18] Hsu, K.-H., *Project Management: a View of the Body of Knowledge*. Hua Tai Publishing, Taipei, 2006. (in Chinese)

[19] Yu, W. D., Project Management in Practice, 2nd Ed., Chan's Arch-Publishing, Taipei, 2015. (in Chinese)

[20] Gong, D. "Optimization of float use in risk analysis-based network scheduling." *International Journal of Project Management*, 15(3): 187-192, 1997.

[21] Gong, D., Rowings Jr., J. E. "Calculation of safe float use in risk-analysis-oriented network scheduling." *International Journal of Project Management*, 13(3); 187-194, 1995.

[22] Zafra-Cabeza, A., Ridao, M.A., Camacho, E.F. "An algorithm for optimal scheduling and risk assessment of projects." *Control Engineering Practice*, 12(10): 1329-1338., 2004.

[23] Moon, H., Kim, H., Kamat, V.R., and Kang, L. "BIM-Based Construction Scheduling Method Using Optimization Theory for Reducing Activity Overlaps." *Journal of Computing in Civil Engineering*, ASCE, 29(3), DOI: 10.1061/(ASCE)CP.1943-5487.0000342, 2015.

[24] Yi, K. J., Langford, D. "Scheduling-Based Risk Estimation and Safety Planning for Construction Projects." *Journal of Construction Engineering and Management*, 132(6): 626-635, 2006.

[25] Kılıç, M., Ulusoy, G., Şerifoğlu, F. S. "A bi-objective genetic algorithm approach to risk mitigation in project scheduling." *International Journal of Production Economics*, 112(1): 202-216, 2008.

[26] Schatteman, D., Herroelen, W., Van de Vonder, S., Boone, A., "Methodology for Integrated Risk and Proactive Scheduling of Construction Projects." *Journal of Construction Engineering and Management*, 134(11): 885-893, 2008.

[27] Zafra-Cabeza, A., Ridao, M.A., Camacho, E.F. "Using a risk-based approach to project scheduling: A case illustration from semiconductor manufacturing." *European Journal of Operational Research*, 190(3): 708-723, 2008.

[28] Luu, V.T., Kim, S.Y., Tuan, N.V., Ogunlana, S.O. "Quantifying schedule risk in construction projects using Bayesian belief networks." *International Journal of Project Management*, 27(1): 39-50, 2009.

[29] Jun, D.H. and El-Rayes, K. "Fast and Accurate Risk Evaluation for Scheduling Large-Scale Construction Projects." *Journal of Computing in Civil Engineering*, 25(5): 407-417, 2011.

[30] Vanhoucke, M. "On the dynamic use of project performance and schedule risk information during project tracking." *Omega*, 39(4): 416-426, 2011.

[31] Mol, T. *Productive safety management*, Butterworth-Heinemann, Oxford, U.K., 2003.

[32] Huang, C.H., *Construction Management*, Chiu Hua Publishing, Taipei, 1990. (in Chinese)