A Risk-based Critical Path Scheduling Method (II) : A Visual Approach System using BIM

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Abstract

The traditional construction schedule planning methods are mostly based on the project activities list broken down by the experienced engineers who primarily analyze the work content of construction drawings, and the activity durations estimated by simulating the construction process according to the conditions of the construction site. However, such an approach does not only give hard time the new engineers without experience, but is also unable to capture the dynamic risk factors while estimating the construction duration. As a result, the planned schedule is usually inaccurate and ineffective. To tackle the abovementioned problem, this paper presents a BIM-based Visual Risk critical path Scheduling System (BIM-VRcpSS) to assist the construction scheduler in developing a more accurate and effective schedule. The proposed BIM-VRcpSS provides functions of risk-based Critical Path Scheduling Method (R-CPSM) based on seven different risk levels. It also equips the construction schedulers with a 3D BIM visual simulation tool to better estimate the activity durations compared with the traditional 2D approaches. Moreover, with the aid of a cloud data based system, the construction schedulers are able to fine-tune duration estimates by considering the impacts of different risk factors without spatial and time limitations. As such, the proposed BIM-VRcpSS can increase the duration estimation accuracy of construction activities, and improve the traditional scheduling approaches.

Keywords –

Risk management, BIM, Construction scheduling and control.

1 Introduction

The prevailing construction scheduling method is the Precedence Diagramming Method (PDM) based on the traditional Critical Path Method (CPM). To conduct a PDM scheduling, the experienced engineer has first to develop a Work Breakdown Structure (WBS) based on previous projects [1]. The activity duration is then estimated by dividing the work quantity by the productivity rate. Such a traditional scheduling method is difficult to adopt by junior staffs without sufficient experience. Moreover, the complex risk factors that affect the activity duration significantly couldn't be taken into account effectively.

Thanks to the recent development of Building Information Modeling (BIM), the execution and planning efficiency of construction works have been greatly improved [2]. Previous research found that the application of BIM did not only facilitate the analysis but also improve the planning and control of a complex construction site.

The current research aims at developing a BIM-based Risk Visual critical path Scheduling System (BIM-VRcpSS) combining a previous developed Risk-based Critical Path Scheduling System (R-CPSS) and the visualization of BIM. The rest of the paper is presented in the following manner: the related works are reviewed first; it is followed by the revisit of the previous developed R-CPSS; then the BIM-VRcpSS is proposed for visualization improvement of R-CPSS; the application of the proposed BIM-VRcpSS is then demonstrated using a real world project; finally, conclusions and recommendations are summarized at the end of the paper.

2 Review of Related Works

2.1 Integration of Risk Management and Scheduling

A risk of a project was defined as the negative impact to the project's objectives. As the occurrence of a risk is associated with a probability, the major tasks for risk management are to measure the occurrence and impact associated to a risk event and the plan the required actions to mediate its impact to the project goals [3].

There have been many researchers engaged in the integration of risk management and construction scheduling. Gone *et al.* [4] proposed a time-disturbance analysis method to optimize the utilization of activity floats, so that the delay of the project schedule can be minimized; Zafra-Cabeza *et al.* [5] adopted a "p-timed Petri net" to represent the risk measure of an activity and developed a method to reduce the impact of risks; Yi and Langford [6] analyzed the safety disasters occurred in the past to develop a safety planning method for the project safety manager to focus on the concentration of safety risks in the project. Kilic *et al.* [7] proposed a Genetic Algorithm to optimize the multi-objective optimization problem of project scheduling, considering four attributes: indirect costs, operation costs, risk reduction costs, and delay punishment costs; Schatteman *et al.* [8] proposed a computer-aided risk management system to identify, analyze, and quantity the major risk factors, and to estimate their impacts to the project schedule so that risk reduction actions are planned; Zafra-Cabeza *et al.* [9] conducted a Monte Carlo simulation of High-tech factory construction project using risk optimization techniques to optimize project cost and schedule.

Beside the above literature, the work done by Yi and Langford [6] attracts our attention the most. Their work considers the construction activity as an integration of many attributes including the construction processes, human resources, technological factors, and the environmental factors. Therefore, the risk of an activity can be expressed in the following equation:

$$\text{Total Risk} = P \times H \times T \times E \tag{1}$$

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 factor 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 [6].

2.2 Integration of 3D Modeling Techniques and Scheduling

There were some works published by previous researchers on integrating 3D modeling in construction scheduling to improve the drawbacks of the traditional human-experienced based scheduling methods. Shan *et al.* [10] used the Visual Basic for Application (VBA) of MS Excel and BIM to develop a project scheduling system that considered the temperature and humidity factors; Moon *et al.* [11] developed a systematic schedule simulation system to minimize overlapping activities for the enhancement of a project's operational performance by integrating fuzzy set, GA, risk factors, and BIM; Hijazi *et al.* [12] proposed a BIM-based 4D simulation method to assess the constructability of a building construction project so that the construction schedule can be improved. Other BIM-based scheduling systems including Chen *et al.* [13], Kim *et al.* [14], and Zhou *et al.* [15]; all of these BIM-based systems utilize the 3D visualization functions to facilitate the construction schedulers in developing a more accurate project schedule.

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-CPSM.

3.1 The Seven Risk Levels of Construction Activity Duration

Inspired by the safety planning method proposed by Yi and Langford [6], the risk of the duration of a construction activity can be affected by the integration of the individual risk factors of that activity. It is believed that the spatial restriction of the construction is the essential constraint for the duration to complete an activity. As a result, the estimation of the 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 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 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 unchangeable, there are five categories (*i.e.*, the 5 Ms of construction management) of risks that can be altered by management schemes including: (1) Man—the availability of different required laborers to perform a construction activity; (2) Machine—the availability of different 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 factor, seven risk levels are classified for the duration of a construction activity:

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

$$RD_0 = \frac{\text{Quantity}}{\text{Rate}} \quad (2)$$

Where, "Quantity" is the quantity of product to be produced by the activity; "Rate" is the production 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 the construction activity.

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

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

Where, RD_0 is "base duration of the activity; "Environment Effect" the extra duration caused by the physical environment risk estimated by the experienced engineer; and 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~Level-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:

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

Where, M_x represents the the most significant resource risk factor in a specific resource type (*e.g.*, M_1 means the most significant risk factor for human resource, M_2 means the most significant risk factor for machine resource, 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:

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

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-CPM 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 primary R-CPM 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 Construction Scheduling based on R-CPSM

In order to implement the concept of the proposed R-CPSM, a computer program was developed named Risk-based Critical Path Scheduling System (R-CPSS). The functions of R-CPSS consist of: (1) Project Creation— create basic information for a construction project; (2) Location Definition — define the spatial information for the construction site; (3) Activity Definition－create the activity list for the WBS of the project, and the quantity of the items for estimating base duration; (4) Relationship Connection － connect the activities according to their sequential relationships; (5) Risk Item Breakdown) － establish the risk item list (including probability and impact information) according to the risk breakdown structure of the project ; (6) Risk Allocation－assign risk items to each of the activities; (7) Information Check － check the completeness of the correctness of information including spatial information and the sequential logic before scheduling calculation; (8) Risk Duration Calculation － calculate the activity duration for each risk level, RD_x, using Equation (2)~(6) ; (9) Critical Path Method (CPM) Calculation － conduct CPM calculation for the project according to the seven risk level of durations for each activity; and (10) Diagram Drawing－draw PDM, EADM, and Bar Chart using the scheduling data.

The Earned Value (EV) curves of the seven risk levels for a sample project is shown in Figure 1.

Figure 1 Output of R-CPSS: EV curves of the 7 risk levels

3.3 Management Suggestions for Different Risk Levels

The suggested management actions for different risk levels shown in Figure 1 are depicted in Table 2.

Table 2 Suggested action for the different risk scenarios

No..	Range	Status	Suggested Action
1	$EV<PV_0$	Good	No
2	$PV_0 \leq EV<PV_1$	Good	No
3	$PV_1 \leq EV<PV_2$	Good	Monitor
4	$PV_2 \leq EV<PV_3$	Medium	Control
5	$PV_3 \leq EV<PV_4$	Medium	Contingency
6	$PV_4 \leq EV<PV_5$	Poor	Fall back
7	$PV_5 \leq EV<PV_6$	Poor	Work around

8	$PV_6 \leq EV$	Out of control	Re-plan

From Table 2, no actions are suggested for the project managers while the EV is below Risk Level-1 (*i.e.*, curve PV_1). Regular project monitoring activities (*e.g.*, EVM indexes, risk monitoring, etc.) are suggested when PV_1 (Risk Level-1) $\leq$ EV < PV_2 (Risk Level-2). Appropriate project control activities (*e.g.*, corrective, preventive, and defect repair actions) are suggested when PV_2 (Risk Level-2) $\leq$ EV < PV_3 (Risk Level-3). The contingency activities are suggested when PV_3 (Risk Level-3) $\leq$ EV < PV_4 (Risk Level-4). The fallback plan is suggested when PV_4 (Risk Level-4) $\leq$ EV < PV_5 (Risk Level-5). The work-around plan is suggested when PV_5 (Risk Level-5) $\leq$ EV < PV_6 (Risk Level-6). The project should be re-planned when PV_6 (Risk Level-6) $\leq$ EV.

4 BIM-based Visual Risk critical path Scheduling System (BIM-VRcpSS)

Based on the R-CPSS presented in Section 3, a BIM-based Visual Risk critical path Scheduling System (BIM-VRcpSS) to enhance the R-CPSS in facilitating construction project scheduler for developing a more accurate and realistic schedule. This section describes the development and verification of the proposed BIM-VRcpSS.

4.1 System Planning of BIM-VRcpSS

The proposed BIM-VRcpSS is developed based on the API provided by Autodesk Revit® 2015 under Microsoft Window7® using Microsoft C# (.Net 4.5) programming language. There are four modules in the BIM-VRcpSS:

- Project Function Module－providing functions for: User Login; Knowledge Management (to retrieve the previous project information related to specific resource risk; and Project Scheduling (to activate R-CPSS system).
- Element Function Module－providing functions for: Activity Selection (select the activities to manipulate); Element Risk (search for risk information and previous cases); Element Rate (the productivity rate associated with BIM elements); Activity Assign (assign the selected BIM elements to specific activity); Element Clear (cancel the BIM element assignment); Hide by Activity (hide the associated BIM element of a specific activity); Show by Activity (show the associated BIM element of a specific activity); Action Activity (Conduct 4-D construction process simulation for the selected activity).
- 4D Model Function Module－providing functions for: Configure Manager (the attribute information management for Category, Family and Symbol); Model Clear (hide the object according to the parameter information); Model Reset (restore all BIM objects); Model Modify (modify BIM objects according to the floor, type, family, and category); Step Action (step by step simulation of construction process).
- Scheduling Function Module－providing functions for: Schedule Simulation (conduct 4-D simulation based on the scheduling data); Stop Simulation (force the 4-D simulation to terminate); Continue Simulation (resume the 4-D simulation that was terminated); Next Activity (proceed the simulation to next activity).

The user interface of the proposed BIM-VRcpSS is shown in Figure 2.

Figure 2 Functions of BIM-VRcpSS

4.2 Knowledge Bases of BIM-VRcpSS

There are two knowledge bases developed for the proposed BIM-VRcpSS: the first is the knowledge base of activity duration risks of historical projects; the second is the productivity rate database for the activities of historical projects. The objective of former is to provide a source for quick search and retrieval of resource risks associated with a specific activity in order to facilitate duration calculation for different risk levels; while the latter aims to serve as a basis for base duration calculation.

There are 9 fields in a risk category dataset: (1) RDID—the identity No. of a risk type; (2) RCode—the code of a risk type; (3) RName—the name of a risk type; (4) RType—the category of a risk type; (5) RRatio—the probability of a risk type; (6) REffect—the effect on activity duration of a risk type; (7) RatioA—the probability of a risk type in the early stage of a project; (8) RatioB—the probability of a risk type in the medium stage of a project; (9) RatioC—the probability of a risk type in the late stage of a project.

There are 6 fields in a BIM object database: (1) RCID—the identity No. of a BIM object; (2) Category—the category of a BIM object; (3) BuiltInCategory—the category of a system buit-in BIM object; (5) Family—the family of a BIM object; (6) Symbol—the sub-category of a BIM object. The primary objective for the BIM object database is to provide an automated searching function. That is that if we assign a BIM object the risk item parameters, then we can retrieve the risk information automatically with the BIM object.

Finally, the productivity rate dataset is set to comprising 5 fields: (1)AutoID—the serial number of an activity; (2)RCID—the ID of object classification; (3)Rate—the productivity rate of an activity; (4)Parametric—the parameter name; (5)Memo—the description of the duration risk. The Entity Relationship Diagram (ERD) of the three datasets are shown in Figure 3.

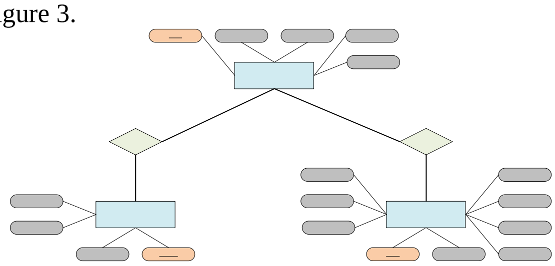

Figure 3 The Entity Relationship Diagram (ERD) of the three datasets

4.3 Application of BIM-VRcpSS

In order to demonstrate the functionality of the proposed BIM-VRcpSS, a real building construction project is adopted for system testing. The selected case is the Spa House Building of the Spring Resort located in Ruisui Township, Hualien of eastern Taiwan. The Spa House is a three-story (28m high) building with one-floor basement. Total floor area is 10,165m^2. Figure 4 shows the 3D model of Spa House Building.

Figure 4 the 3D model of Spa House Building

The system testing procedure is elaborated in the following:

- Step-1: User Login—the project is named "International Tourist Hotel"
- Step-2: Spatial planning for construction areas—Area-A (left building), Area-B (central building), Area-C (right building), All (A+B+C), Interior of A&C.

LID	LCode	LExtend	LName	LMemo
0	Site	-	Site	
100	A	-	Left Hotel	Left
150	A	Inside	Left Hotel Inside	
200	B	-	Center	
250	B	Inside	Right Hotel Inside	
300	C	-	Right Hotel	Right
400	All	-	Area	

Figure 5 Spatial configuration of the case building

- Step 3: Create Activity List—the activity list of the project consists of mobilization, excavation, Raft Foundation Construction (Area A, B & C), B2F Construction (Area A, B & C)、B1F Construction (Area A, B & C), 1F, 2F, 3F, 4F, PF, RF Steel Structure, Exterior Wall (I), Exterior Wall (II), Exterior Door and Windows (I), Exterior Door and Windows (II), M&E (I), M&E (II), Interior, and Clean up. All of the activities are input into the database of BIM-VRcpSS.

AID	ACode	AName	ADuration	AType	LID
100	S-001	Mobilization	4	Normal	0
200	S-002	EarthWorks I (Cut)	4	Normal	0
300	S-003	Earthworks II (Fill)	3	Normal	0
400	S-004	Demobilization	4	Normal	0
1000	FD-001	Foundation Left	5	Normal	100
1100	FD-002	Foundation Center	7	Normal	200
1200	FD-003	Foundation Right	5	Normal	300
2000	SB2-001	B2F Structure Left	5	Normal	100
2100	SB2-002	B2F Structure Center	7	Normal	200
2200	SB2-003	B2F Structure Right	5	Normal	300
3000	SB1-001	B1F Structure Left	5	Normal	100
3100	SB1-002	B1F Structure Center	7	Normal	200
3200	SB1-003	B1F Structure Right	5	Normal	300
4000	S1-001	1F Structure	5	Normal	400
4100	S2-001	2F Structure	5	Normal	400
4200	S3-001	3F Structure	5	Normal	400
4300	S4-001	4F Structure	5	Normal	400
4400	SP-001	PF Structure (P1,P2)	5	Normal	400
5000	SR-001	RF Steel Structure	4	Normal	400
6000	AO-001	Outside Wall I	5	Normal	100

Figure 6 Activity list of the case building

- BIM Model Development — building the BIM model for the case building from bottom to top including the temporary facility models. During the BIM model development process, the BIM objects are first assigned to the selected activity; then the potential risks associated with the activity is identified using a knowledge management system (KMS); finally, the base duration of the selected activity is automatically calculated using the quantity provided by the BIM model to be divided by the productivity rate retrieved from database. The base duration of each activity is also shown in Figure 6.
- Connect Activities — the sequential relationships among the activities are determined according to the task groups, trades, and work areas. The results are shown in Figure 7.

AID	ACode	AName	PreID	PreCode	PreName	Relation	Lag
200	S-002	EarthWorks I (Cut)	100	S-001	Mobilization	FS	0
300	S-003	Earthworks II (F...	3200	SB1-003	B1F Structure Right	FS	0
400	S-004	Demobilization	7100	M-002	MEP II	FS	0
1000	FD-001	Foundation Left	200	S-002	EarthWorks I (Cut)	FS	0
1100	FD-002	Foundation Center	200	S-002	EarthWorks I (Cut)	FS	0
1200	FD-003	Foundation Right	200	S-002	EarthWorks I (Cut)	FS	0
2000	SB2-001	B2F Structure Left	1000	FD-001	Foundation Left	FS	0
2100	SB2-002	B2F Structure Ce...	1100	FD-002	Foundation Center	FS	0
2100	SB2-002	B2F Structure Ce...	2000	SB2-001	B2F Structure Left	FS	0
2200	SB2-003	B2F Structure Right	1200	FD-003	Foundation Right	FS	0
2200	SB2-003	B2F Structure Right	2100	SB2-002	B2F Structure Ce...	FS	0
3000	SB1-001	B1F Structure Left	2200	SB2-003	B2F Structure Right	FS	0
3100	SB1-002	B1F Structure Ce...	3000	SB1-001	B1F Structure Left	FS	0
3200	SB1-003	B1F Structure Right	3100	SB1-002	B1F Structure Ce...	FS	0
4000	S1-001	1F Structure	300	S-003	Earthworks II (F...	FS	0
4100	S2-001	2F Structure	4000	S1-001	1F Structure	FS	0
4200	S3-001	3F Structure	4100	S2-001	2F Structure	FS	0
4300	S4-001	4F Structure	4200	S3-001	3F Structure	FS	0
4400	SP-001	PF Structure (P!...	4300	S4-001	4F Structure	FS	0
5000	SR-001	RF Steel Structure	4400	SP-001	PF Structure (P!...	FS	0

Figure 7 Sequential relationships among the activities

- Assign Activity Risk—review the automated risk assignment during BIM model development, new risks can be assigned should there be other risk factors. The results are shown in Figure 8.

AID	ACode	AName	RID	RCode	RName	RType	RRatio	REffect
100	S-001	Mobilization	100	Site	Site (General)	Environment	10	2
100	S-001	Mobilization	1000	Labor	Labor (General)	Men	10	1
100	S-001	Mobilization	2000	Machine	Machine (General)	Machine	10	1
100	S-001	Mobilization	3000	Material	Material (General)	Material	10	1
100	S-001	Mobilization	4000	Method	Method (General)	Method	10	3
100	S-001	Mobilization	5000	Money	Money (General)	Money	5	1
200	S-002	EarthWorks 1 (Cut)	100	Site	Site (General)	Environment	10	2
200	S-002	EarthWorks 1 (Cut)	1000	Labor	Labor (General)	Men	10	1
200	S-002	EarthWorks 1 (Cut)	2500	Excavator	Excavator (General)	Machine	10	1
200	S-002	EarthWorks 1 (Cut)	3000	Material	Material (General)	Material	10	1
200	S-002	EarthWorks 1 (Cut)	4000	Method	Method (General)	Method	10	3
200	S-002	EarthWorks 1 (Cut)	5100	Money-5	Money 1/5	Money	5	1
300	S-003	Earthworks 11 (F...	100	Site	Site (General)	Environment	10	2
300	S-003	Earthworks 11 (F...	1000	Labor	Labor (General)	Men	10	1
300	S-003	Earthworks 11 (F...	2500	Excavator	Excavator (General)	Machine	10	1
300	S-003	Earthworks 11 (F...	3000	Material	Material (General)	Material	10	1
300	S-003	Earthworks 11 (F...	4000	Method	Method (General)	Method	10	3
300	S-003	Earthworks 11 (F...	5100	Money-5	Money 1/5	Money	5	1
400	S-004	Demobilization	100	Site	Site (General)	Environment	10	2
400	S-004	Demobilization	1000	Labor	Labor (General)	Men	10	1

Figure 8 Risk assignment for the activities

- Result Checking — Simulate the construction process step-by-step to ensure the correctness and appropriateness of the visual construction model until no more error.
- Output Results — Conduct R-CPSM calculations for all risk levels using BIM-VRcpSS, draw the PDM and other diagrams based on the scheduling data generated by the BIM-VRcpSS. Figure 9 shows the calculated early start/finish network diagram for the case project. Figure 10 shows the 7 EV curves for the seven risk levels.

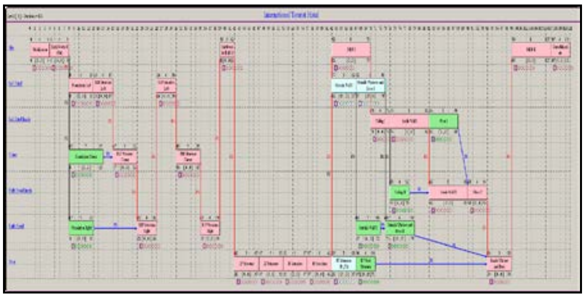

Figure 9 The precedence diagram for the case project.

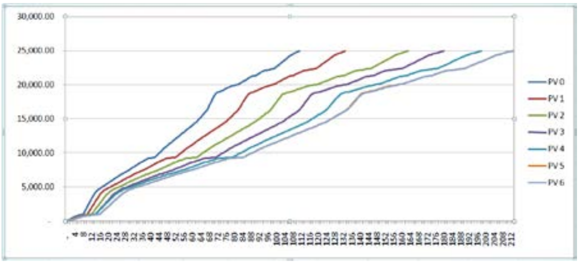

Figure 10 The 7 EV curves for the seven risk levels.

5 Findings

The proposed BIM-VRcpSS provides seven EV curves for the seven risk levels, instead of the traditional CPM's single EV curve. It uncovers the unknown risk facing construction project managers in planning a more realistic construction schedule when the traditional CPM and EVM are adopted. In the following, some profound findings are discussed for reference of the practitioners in construction industry project scheduling while planning a construction project:

- More risk scenarios for risk based scheduling—the proposed BIM-VRcpSS calculates the activity schedule data according to different risk levels of the activity, and developed 7 different critical paths. Such critical path (of different risk level) provides the schedulers more information to plan and control their construction project. If *de facto* network has differed from its original plan (the PV), then the proposed BIM-VRcpSS shows the project manager "how bad the progress is?" and "what will result if no effective action is taken."
- Could knowledge base for risk assessment—the proposed BIM-VRcpSS allow construction scheduler to revise the activity risk data by accessing cloud knowledge base. It is therefore the most updated and ever-accumulative source of risk knowledge for future schedule planning.
- Cloud productivity rate data base—similar to risk knowledge base, the proposed BIM-VRcpSS allow construction scheduler to revise the activity risk data by accessing cloud productivity rate database. The productivity rate data provide the BIM-VRcpSS the automatic calculation of base activity duration. It can be updated at a real-time basis to ensure the correctness and timeliness of the retrieved productivity rate data.
- Visualization of construction schedule—contrast to the traditional scheduling method that was primarily based on interpretation of the 2D construction drawing information to develop the construction schedule, the proposed BIM-VRcpSS adopts 4D functions of BIM platform. It is easier for user to visualize the spatial and environmental constraints of a construction site, which will significantly improve the efficiency of construction scheduler's work.
- Providing a tool for schedule risk control—from Figure 9 and Table 2, *de facto* EV curve can be compared with the seven PVs to determine which risk scenario the project is currently experienced. The suggested management actions provide the construction project managers a more clear direction for improve the schedule performance of his/her project. Such a function has not been found in literature.

6 Conclusions and Recommendations

6.1 Conclusions

This paper presents the results of a research on the development of a BIM-based Visual Risk critical path Scheduling System (BIM-VRcpSS) to assist the construction scheduler in developing a more accurate and effective schedule. By combining the visualization of BIM, the proposed BIM-VRcpSS provides the construction schedulers a more powerful tool to better capture the nature of risks associated with a construction activity during the construction process.

A Risk-based Critical Path Scheduling Model (namely R-CPSM) considering seven different risk levels of activity duration is developed to model the risk scenarios of a construction activity. The proposed BIM-VRcpSS provides a visual tool that makes the implementation of R-CPSM more realistic and practical.

In addition to visualization of duration risks of an activity, the proposed BIM-VRcpSS also improve the scheduling process by offering the scheduler a 3D visual model (instead of the traditional 2D drawing), which helps develop a more accurate construction schedule.

Finally, the 7 EV curves (instead of the single EV curve in the traditional EVM) for the seven risk levels generated by the proposed BIM-VRcpSS provides the construction scheduler a better overview of *de facto* construction schedule performance. It can be maintained and updated on real-time so that the true situation of the project can be better monitored and controlled.

6.2 Recommendations

Some directions after the current research are recommended as follows:

The output chart in current version of BIM-VRcpSS is developed within MS Excel, a self-contained system can be developed to be more portable and efficient.

The proposed BIM-VRcpSS is an EVM-based project monitoring system. It quotes similar limitations of the traditional EVM systems. Future works can be engaged in developed an Earned Duration Management (EDM) based project monitoring system.

7 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.

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