SIMPLIFIED SIMULATION APPROACH TO MANAGING SCHEDULE-OVERRUN RISKS IN CONSTRUCTION OPERATIONS

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ABSTRACT : The complex and dynamic job nature and the ever-changing working environment of construction projects inevitably present uncertainties to construction operations. Identification, evaluation and control of uncertainties constitute main elements of risk management and critical tasks of project management in construction. This paper is focused on application of a simplified discrete-event simulation approach in management of schedule-overrun risks, each being the combination of the occurrence probability of an uncertain interruptive factor and its potential consequence in terms of time delay. A case study observed from a concreting operation in Hong Kong is converted into a simulation model and analyzed with an in-house-developed simulation package for demonstrating how the proposed approach can be implemented to manage multiple schedule-overrun risks on construction projects.

Key words : Schedule, Operations Simulation, Risk Evaluation, Risk Management, Operation Interruptions

1. INTRODUCTION

Uncertain interruptive factors are inevitable in construction projects owing to the complex and dynamic job nature and the ever-changing working environment of construction. Laufer and Stukart [1] surveyed 40 US construction managers and owners, indicating that at least 65% of projects were considered as having medium to very high uncertainty at the planning state of construction. Kangari [2] piloted a survey to investigate the risk management perceptions and trend in US. The survey result showed that many construction practitioners admitted the inherent features of construction projects contribute to different uncertainties in the construction phase. It is always desired a systematic way to manage the uncertainties in order to run a construction project within project deadline and budget.

Risk is defined as a combination of the probability of a deteriorating event and its consequence [3]. In this paper, schedule-overrun risk is defined as a combination of the occurring probability of an uncertain interruptive factor and its consequence in terms of time delay, possibly resulting in schedule overrun for the whole project. Identification, evaluation and control of risks constitute the main elements of risk management [4]. Figure 1 illustrates a complete risk management cycle. The first part in the risk management cycle is the risk analysis representing a detailed study on working procedures so as to identify potential deteriorating factors in the work system and estimate the likelihood of occurrences and immediate impacts of these factors on the system. Following the risk analysis is the risk evaluation in which the ultimate consequence upon the work system is evaluated when risks associated with multiple uncertain factors manifest themselves at different levels. Note that the risk level of an uncertain factor is measured by the probability rate of occurrence and the severity of the immediate consequence. The risk analysis and risk evaluation together are called risk assessment and form a basis for the risk control in which control measures are devised and implemented, aiming to relieve the ultimate unpleasant consequence. Since the implementation of risk control measures could affect the existing work system, the enforcement of risk control measures initiates another round of risk assessment (the arrows pointing back to "Risk Analysis" and "Risk Evaluation" from "Risk Control" in Figure 1).

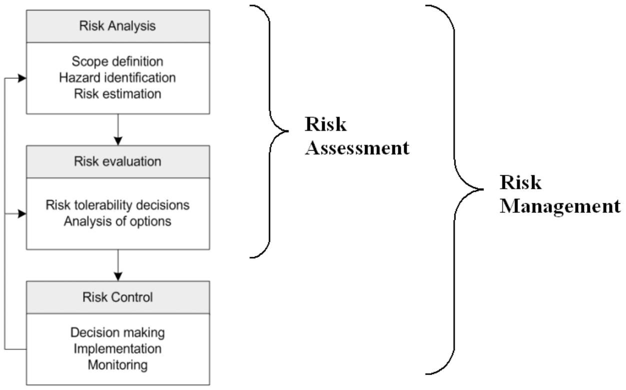

Figure 1. Flowchart of a typical risk management cycle

To facilitate the management of schedule-overrun risks in construction, many previous research applied quantitative methods to perform risk assessment. One of the established schedule-overrun risk evaluation techniques is PERT, the Project Evaluation and Review Technique. PERT was developed in mid-1950s by the US Navy Special Project Office aiming to incorporate uncertainties in critical path method (CPM) network scheduling so as to estimate the total project duration in a more statistical way through simple hand calculation.

Many researchers [5-8] developed different schedule-overrun risk management methods and tools based on the PERT. The first use of PERT on schedule risk analysis can be traced back to 1983. In this year, the project management group at UMIST developed a computer program to test the effect of risks on cost and duration of a barrage construction project. This computer program was setup based on the PERT, and the Monte Carlo techniques were applied to calculate the cumulative effect of uncertain durations of individual activities on the whole project [5]. However, PERT was recognized insufficient to be the ideal schedule risk management technique because of its inherent disadvantages, such as:

1) PERT is incapable to consider resource constraints
2) PERT is inefficient to deal with repetitive activities
3) PERT is difficult to synchronize the analysis of multiple concurrent risk factors

As an alternative to the PERT, discrete-event simulation takes into account the resource interactions and provides a virtual construction system for the analysis and improvement of real operations through experiments on the computer model [9]. Some previous research has already demonstrated the applicability and usefulness of simulation on construction projects such as earth-moving and tunneling [10-11].

The capability of modeling dynamic and interactive construction work systems as well as the ability to model schedule-overrun risks make discrete-event simulation a desired tool for schedule-overrun risk management. Bernold [12] carried out experiments on a concrete placing system in which a concrete vibrator was set with a defect. The result showed that the breakdown risk imposed by the vibrator defection affected the productivity and total cycle time. However, Bernold did not apply his simulation experiment results on schedule-overrun risk management by mapping the relationship between the resource breakdown factors and the schedule-overrun consequence. Damrianant & Wakefield [13] incorporated resource breakdowns and other delay factors in Petri-Net models by inserting new model elements to control the probability rates and consequences of resource breakdowns and some other delay factors. Yet, it is noted that the proposed method made the Petri-Net model structure more complicated and there was no application of their augmented Petri-Net model on schedule-overrun risk management found in the paper. In short, practitioners have yet to make full use of this unique tool and apply it on the schedule-overrun risk management.

In this research, we employed a simplified discrete-event simulation approach (SDESA) in an attempt to facilitate schedule-overrun risk management, with particular emphasis on how to evaluate risks and assist practitioners in establishing risk control guidelines. A case study observed from a concreting operation in Hong Kong is converted into a model and analyzed by an in-house-developed SDESA simulation package so as to demonstrate how the proposed approach is applied in managing schedule-overrun risks in construction operations.

2. METHODOLOGY

The in-house-developed simulation package of SDESA was used in the case study. SDESA features simplified simulation algorithms and streamlined model structures such that simulating construction systems can be made as easy as applying CPM. Modelers create a computer model of the real system in a simple and straightforward fashion in SDESA based on real life statistics and then they can experiment on the model to effectively evaluate and improve their construction methods [14].

Interruptive factors, such as resource breakdown and unexpected activity stoppage, are quantified as the combination of its occurring probability and its downtime duration in SDESA. This allows the direct adaptation of the data collected for risk analysis to inputs of a SDESA model. The occurring probability (Prob_Intrpt) of an interruptive factor is represented by a decimal between 0 and 1 such that 0 stands for no chance to happen and 1 stands for certainty of happening; while downtime duration (Intrpt_Dur) means the resultant delay time for the work task when the interruptive factor manifests itself during construction and is represented by a constant value or a statistical distribution. The SDESA's executive program is responsible for checking whether the prescribed risk factors would materialize when the activity is activated. For instance, when the activity is just about to start, the executive first generates a random number (RND) between 0 and 1, and if the random number is smaller than the interruption probability (Prob_Intrpt), the defined downtime duration (Intrpt_Dur) will then be scheduled and inserted to the activity randomly between the original activity begin time (BT) and end time (ET) (Figure 2).

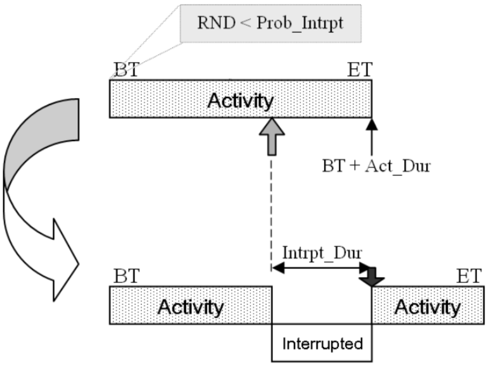

Figure 2. Illustrative bar chart showing how an interruption is inserted into activity

Similar input interfaces and processing mechanisms are also applicable for defining the breakdown property of resources. In SDESA, a resource can have specific breakdown probability rate (Prob_Brk) and breakdown duration (Brk_Dur) for working on a particular activity. The SDESA executive will handle a resource breakdown in a similar way as an activity interruption when an activity requests a resource with a non-zero Prob_Brk prescribed. In reality, more than one interruptive factor can happen in parallel or partially overlap and the effects of concurrent interruptive factors are carefully modeled in SDESA. For instance, suppose there are two interruptive factors happen on the same activity such that the first interruptive factor breaks out at 2:00pm and this interruption lasts for 3 hours (i.e. 2:00-5:00) while the second interruptive factor breaks out at 4:00pm and last for 4 hours happening (i.e. 4:00-8:00). The overlapped effect of these two concurrent interruptions is equivalent to that of a single interruption occurring on the activity from 2:00pm to 8:00pm.

Besides uncertain interruptive factors, modelers can also specify foreseeable prescheduled interruptions in SDESA to represent any halt or delay on an activity, such as lunch break or tea break, and regular equipment maintenance, by specifying the start and end times of those interruptions [15].

3. THE CASE STUDY

The case study is a real hoist and barrow concreting operation (Figure 3) observed from a Hong Kong building site in 2002. The data was collected by (1) on-site observation with a digital stop watch, (2) referencing the concrete truckmixer delivery slips, and (3) interviewing the site foremen and engineers.

The “Hoist and Barrow” concreting operation used a hoist for vertical transportation of concrete in a skip container. At the beginning of the concreting operation, a truck-mixer full of concrete arrived at the site and parked close to the feeding tip of the skip. The truckmixer then unloaded concrete into the skip to its full capacity. Upon receiving a “request concrete” signal from the upper floor, the skip controller switched on the hoist at the ground level. When the skip reached the upper floor, it tipped concrete into the opening of a hopper. The skip then returned down the hoist to ground level. The truck unloading and skip hoisting processes repeated on the receipt of each “request concrete” signal. Once the hopper at the upper floor was filled, the laborers maneuvered wheelbarrows (barrowman) along temporary timber paths, collecting and pouring concrete into the formwork of a slab. The barrowman’s work cycle was readily identified, i.e. collecting concrete into wheelbarrows, traveling to the pour location, placing concrete in formwork, traveling back to the hopper, and collecting concrete from the hopper again. Once the hopper was empty, the barrowmen simply pressed a bell button to alarm the controller at ground level, requesting another skip-load of concrete. Once the truck-mixer was emptied, it left the unloading bay and moved to the washing bay, where the truck was cleaned before leaving the site (Figure 3).

Figure 3. Photo of the Hoist & Barrow concreting site

The concreting operation was converted into a SDESA model (Figure 4) based on the site observation. The time distributions of the activities used in the base-case scenario for simulation are listed in Table 1. The time distributions in the table were fitted based on the normal activity times collected during the site observation. Note that the normal activity time means the time sample of an activity when the activity is not affected by any interruptive factor. The base-case scenario was setup for the model validation and verification purpose. Different levels of interruptive factors were added to the base-case scenario in order to examine their ultimate consequence to the concreting system in terms of extensions to the total operation duration.

Table 1. Time Distributions of the Activities in the Base Case Simulation Model

Activities	Time Distribution
Truck park into the site and setup	1.5 – 3.5 (Uniform)
Unload concrete to skip	0.3, 0.9, 0.6, 1.9 BETA (L,U,a,b)
Hoist up skip	0.25 (Constant)
Pour concrete to hopper	0.14 (Constant)
Skip return to G/F	0.25 (Constant)
Barrowman collect concrete	0.1, 0.4, 1, 3.2 BETA (L,U,a,b)
Barrowman travel to dump	0.2, 0.4, 10.2, 10.3 BETA (L,U,a,b)
Barrowman dump concrete	0.03, 0.18, 4.2, 5.2 BETA (L,U,a,b)
Barrowman return to collect	0.2, 0.4, 1.4, 1.7 BETA (L,U,a,b)
Truck washing	2 – 2.8 (Uniform)
Truck Leave Site	0.5 – 1.25 (Uniform)

The SDESA model (Figure 4) is composed of three work flows, i.e. the truckmixer, the skip, and the wheel barrow. These work flows are all initiated by flow entities (the diamond blocks in Figure 4), which undergoes a sequence of activities (the rectangular blocks in Figure 4) linked up by arrows, in the way similar to the CPM. Flow entities represent work units when the work flow is open-ended and material-handling resources when the work flow is in loop, respectively. The first flow, Truckmixer, is open-ended such that the 14 flow entities stands for 14 truckloads of concrete as required to be processed. The work flows for "Skip" and "Wheel Barrow" are in loop forms, so the corresponding flow entities stand for the resource skip and wheel barrowman respectively. For one activity, the resources required to perform the activity are shown in the top-left corner of the activity block, with resources released upon finishing the activity marked in the top-right corner. Looking at the first flow in the model (Figure 4), one parking bay (1 PARK-BAY) is requested at activity "1: Park & Setup", and released at the end of activity "3: Leave Site". Note activity "1: Park & Setup" also requires the availability of the record labor (RL). To initialize the activities in the second flow, the disposable resource entities 10 SL are generated at the end of "1: Park & Setup", representing 10 skip loads are ready to be hoisted to the concreting floor. Disposable resource entities are consumed after the execution of the activity and are marked with a "+" prefix (e.g. 1 +SL). The size limit of the present paper does not allow an elaboration of the SDESA methodology and the whole model, and readers are suggested to refer to the SDESA user manual [15] for more information.

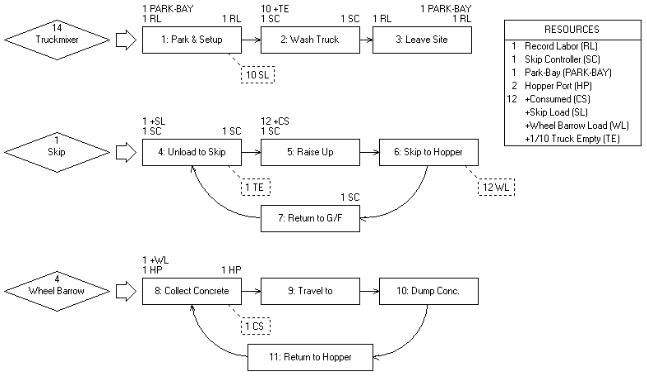

Figure 4. SDESA Model for the Hoist and Barrow Concreting Operation

3. MODEL VALIDATION & VERIFICATION

The SDESA model was validated by comparing the process cycle time–resulting from simulation– to the site observation records. The 28.5 minutes mean cycle time for unloading one truckmixer was obtained from 100 Monte Carlo duplications of running the SDESA model. The output from the model was close to the time data collected from the site, e.g. the shortest cycle time 27 minutes was observed on the site. The results suggested that the model for the base-case scenario sufficiently portrayed a smooth, continuous concreting operation cycle with no significant interruptions.

To cross-validate the SDESA simulation model, another model was established by using the well-known simulation tool – CYCLONE [16]. The CYCLONE model was set up in the SIMPHONY template [17]. This CYCLONE model is also comprised of three major loops, i.e. the truckmixer cycle, the skip cycle, and the barrowman cycle (Figure 5), but appears convoluted to comprehend. The first four truckmixers leaving site times as obtained from the CYCLONE model are compared against the results from the SDESA model (Table 2). The close agreement of the outputs from CYCLONE and SDESA models (less than 3% difference) provides strong evidence that the SDESA model is a valid representation of the concreting.

Table 2. The 1st – 4th truckmixer "leave site" times: CYCLONE vs. SDESA-1 for cross-checking (without interruptions); site-observed times vs. SDESA-2 for validation (considering two interruptive factors simultaneously)

Truckmixer	CYCLONE	SDESA-1	Site Observed	SDESA-2
1	28.5	28.3	40	36
2	57.1	56.5	73	63
3	85.6	84.9	111	93
4	114.0	113.1	138	123

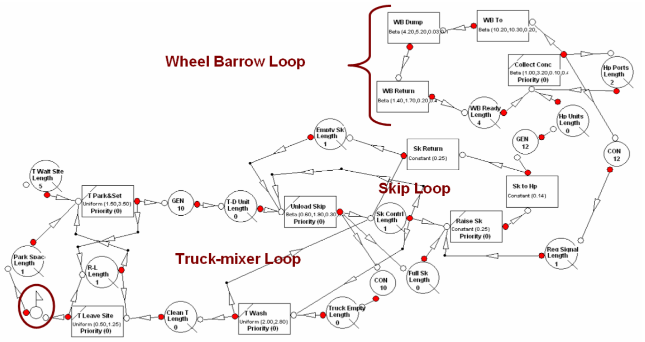

Figure 5. CYCLONE Model for the Hoist and Barrow Concreting Operation

4. SIMULATION EXPERIMENTS

Two interruptive factors – namely, hoist breakdown and site entrance blockage – were considered and entered into the SDESA model for simulation experiment. And the ultimate consequence of a schedule-overrun risk was gauged by the extension to the total operation duration. Hoist breakdown is a typical resource breakdown that leads to a complete halt or a slowdown of the skip transporting process from the ground floor to the concreting floor. Site entrance blockage happens occasionally when other construction materials are being delivered or the street traffic is busy on the site. As a result, the parking and leaving times of truckmixers are lengthened when passing through the site entrance. The normal working hour on the building site was from 8:00am to 6:00pm (10 hours) subject to local regulations. Out of these 10 hours, 30 minutes was spent on the site preparation and site clean-up while 60 minutes and 15 minutes were on the lunch break and tea break respectively. The project manager was most concerned about avoiding overtime because the overtime would lead to double pay to laborers and bring disturbance to neighborhoods around the site.

4.1 Sensitivity Analysis

Different combinations of occurrence probability rates and downtime duration of the two interruptive factors were entered to the base-case model in forming different scenarios (24 scenarios were designed to study the sensitivity of one interruptive factor at a time). The response of the system in terms of the total pour time is indicated by the departure time of the last truckmixer (14th truckmixer). Simulation results from 24 scenarios considering various risk levels for hoist stoppage and site entrance blockage, respectively, are plotted as two 3D-surface charts in Figure 6. The X-axis, Y-axis, and Z-axis represent the occurring probability (Risk-Prob), the interrupted duration (Intrpt_Dur), and the mean departure time of the last truckmixer (M.CDur) respectively. Each point on the surface of the plots represents the average departure time of the last truckmixer as of one scenario. Both 3D charts indicate a trend that total duration of the concreting operations increases when the occurring probability increases or interruption duration lengthens.

Since the two 3D charts in Figure 6 are in the same scale, it is obvious that the concreting system is much more sensitive to the hoist breakdown risk than the site entrance blockage risk, as reflected by the relative steepness (slopes) of the 3D surface plots.

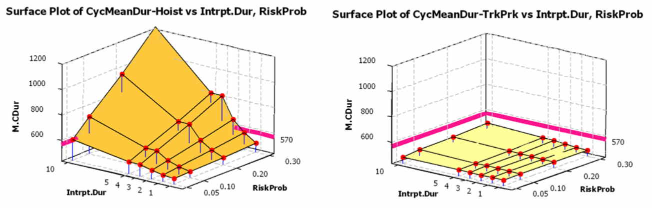

Figure 6. Surface plots of the means leave time of the last truckmixer (Left: Hoist Breakdown; Right: Site Entrance Blockage)

This finding is considered reasonable because the usage of the hoist was 10 times more frequent than the use of the entrance for parking procedures. Under the same breakdown probability rate and duration, a higher activation frequency would materialize more interruptions and hence lead to longer average cycle duration. However, it is noted that not all sensitivities as of schedule-overrun risks could be recognized in such a straightforward way, particularly when the system modeled is complex and have many interactions.

4.2 Defining Risk Control Zones

To clearly map the relationships between the system response and the different risk levels sourced from the hoist breakdown uncertainty, another set of scenarios for the hoist breakdown factor was further designed for experimentation. And the responses are plotted in a contour plot (Figure 7). Note that the system response in the contour plot is no more indicated by the mean departure time of the last truckmixer. Instead, the 80% percentile of the last truckmixer departure time after 100 simulation runs is used. The 80% percentile can be seen as a more conservative mean, indicating that with 80% chance, the concreting job can be completed within the "mean" pour time predicted from simulation.

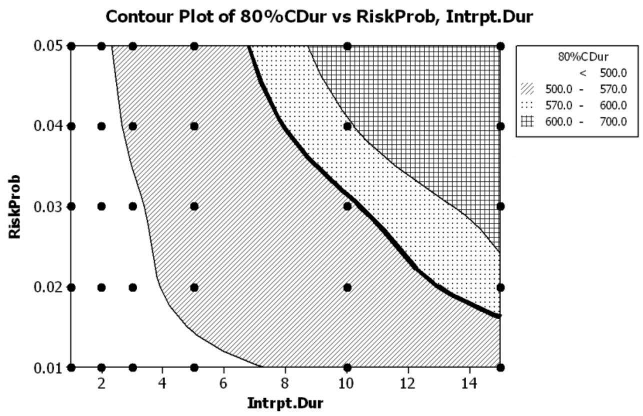

Figure 7. Contour plot of 80% percentile of the last truckmixer leave time for the hoist breakdown risk

The X-axis and Y-axis of the contour plot (Figure 7) are the hoist breakdown duration and probability respectively. Different hatchings in the contour plot are used to represent different ranges of the total pour duration. These different time zones were defined to help the project manager recognize the tolerability of the risk such that proper risk control measures can be arranged in a systematic and informative manner. The "comfort" zone is at the left most one (80%CDur < 500) in the plot, implicating that the hoist breakdown risk has a negligible effect on extending the total cycle duration beyond the 10-hr (600-min) target because the working hour predicted is less than 500 min. Therefore, the project manager can accept the risk and do nothing. The operation schedule has a slight chance to be overrun in the "marginal" zone (80%CDur = 500 – 570) which is immediately next to the "comfort" zone. The "overtime" zone (80%CDur >570) is at the immediately right-hand-side of the "marginal" zone. If the hoist breakdown risk level, reached the area at the right hand side of the reference line, it has an 80% the concreting operation schedule will overrun and the project manager should immediately apply risk control measures, e.g., using the winch to deliver concrete when the hoist is out of order. The project manager could also modify their simulation model to evaluate the efficiency and effectiveness of the proposed risk control measures before implementation.

4.3 Considering Multi-Concurrent Risks

SDESA is capable of dealing with more than one interruptive factor in parallel in a typical construction operations system [18].The modeler may also apply multivariate statistical analysis method (such as the 2k factorial designs) to handle more than one interruptive factor in a simulation model and analyze experimental results from simulation [19]. The outputs from SDESA model (SDESA-2) which simultaneously considered the above two interruptive factors were corroborated by the records actually observed on site (given in Table 2).

5. CONCLUSIONS

The merits of considering resource constraints and handling repetitive activities make discrete-event simulation a better alternative, than PERT, to foresee the total duration of a project or operation. Simulation is proposed to facilitate the risk evaluation process and help practitioners to devise risk control measures. A case study observed from a concreting operation in Hong Kong has been converted into a model and analyzed by using an in-house-developed simulation package SDESA (Simplified Discrete-Event Simulation Approach) so as to demonstrate how the proposed approach is applied in managing schedule-overrun risks at the operation level.

The proposed risk management methodology has the following advantages.

1) Interruptive factors are simply defined by their occurring probability and downtime duration through user-friendly interfaces of the SDESA.

2) Project managers can perceive the sensitivity or tolerability of a certain risk factor in terms of influencing the system objective through designing simulation experiments and hence come up with effective risk control measures.

3) Before the risk control measures are put into practice, the proposed measures can be evaluated in the simulation model such that project managers can select the best one if there are several alternatives.

ACKNOWLEDGMENT

This work described in this paper was substantially supported by a grant from the Research Grants Council of the Hong Kong Special Administrative Region, China (Project No. PolyU 5049/02E).

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