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Construction Risk Management of Irrigation Dams

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Abstract: The timely completion of complex dam-construction projects is a challenging proposition, both in developing and developed countries. Delays are frequent in such projects and impose costly burdens on regional and national economies. One of the main reasons for the delay in those projects is caused by ignoring the uncertainty inherent in the completion of the tasks that arise in dam construction. Project managers often use the critical path method to schedule those activities. A key limitation of this method is that the completion times for activities near the critical path are frequently assessed inaccurately. This paper evaluates the uncertainty of scheduling the tasks associated with the construction of dams, and relies on the Gelal earthfill dam and Khersan 3 concrete dam projects for illustration purposes. An evaluation method based on Monte Carlo simulation and risk management indices is herein proposed. The results of this study are intended to assist project managers and decision-makers in scheduling of construction activities and minimizing associated costs. Results indicate that the probabilities of completing the aforementioned earth and concrete dams on schedule are 65 and 50%, respectively. Moreover, the results demonstrate the importance that the completion times of individual project activities has on overall timely project completion. **DOI: 10.1061/(ASCE)IR.1943-4774.0001001.**

Author keywords: Work scheduling; Uncertainty; Critical path method; Monte Carlo simulation; Risk management; Earthfill dam; Concrete dam.

Introduction

Recent research dealing with water resources management aided by simulation and optimization models and methods encompasses several domains, such as reservoir operation (Ashofteh et al. 2013a; 2015b, c), design operation of pumped-storage and hydropower systems (Bozorg-Haddad et al. 2014), design of levee layouts (Bozorg-Haddad et al. 2015b) and hydrologic analysis (Ashofteh et al. 2013b), qualitative management of water resources systems, (Bozorg-Haddad et al. 2015a), and algorithmic development (Ashofteh et al. 2015a). However, few previous publications have focused on the risk management associated with the construction of irrigation dams.

A main objective of dam-project builders is to achieve project completion on schedule while adhering to the allocated budget. Project delays almost invariably lead to higher project costs. Several works have classified project delays into two main categories: (1) delay analysis, and (2) causes of delay.

Delay is an action or event that prolongs the time required to complete a project beyond the preplanned finish date. Reasons for delays include owner-caused delays (OCD), contractor-caused or consultant-caused delays (CCD), and third-party-caused delays (TPCD). Analysis and causes of delay are addressed in project management investigations.

Morris (1990) estimated cost and time overruns in public sector projects and considered the opportunity cost in terms of the extra capital × time that is used up. Cost overruns (at 80%) and the extra capital × time incurred (about 190%) were very large; even after removing the cost increase due to inflation. Bubshait and Cunningham (1998) investigated delay-analysis methodologies and compared them. They applied a computerized critical path method (CPM) to measure and compare delay impacts on construction schedules. Their results indicated that the outcomes of delay analysis are prone to error, nor can one method of analysis be universally applicable. Kartam (1999) analyzed delay claims using a generic methodology, showing that while there are several techniques for analyzing delay claims, very few of these are considered adequate. Al-Khalil (1999) investigated delays in public utility projects in Saudi Arabia which included the frequency of delayed projects; the extent of the delay; and the responsibility for the delay. Al-Momeni (2000) stated delay reasons for 130 public projects in Jordan with the aim to aid construction managers in establishing adequate performance supervision prior to contract award. The main causes of delay in construction of public projects were related to design flaws, changed conditions, foul weather, late deliveries, financial setbacks, and increases in the scope of project tasks. Odeh and Battaineh (2002) classified the main causes of delays in construction projects from consultants' and administrative managers' viewpoints into eight major groups. Sonuga et al. (2002) cited 11

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reasons for project delays in water and irrigation projects in Nigeria. Williams (2003) described and evaluated standard methods currently available for assessing delays in major projects. Frimpong et al. (2003) studied the reasons of delays and cost increases in groundwater projects in developing countries, with Ghana as a case study. Long et al. (2004) used interviews and a pilot study involving six experts (including a municipal administrator, an employer, a designer, a contractor, and two university professors) to classify the problems of large construction projects in Vietnam.

The World Commission on Dams (WCD), through a complete research of about 99 projects, stated that only half of the projects were completed on schedule and 30% of the projects with 1 to 2 years of delay, and four projects with more than 10 years of delay. The main causes of these delays in projects are financial instability, incompetence of contractor and construction management, unrealistic time scheduling, dissatisfaction of the workforce, and legal and institutional obstacles and challenges.

Management of a dam construction project reflects the uncertainty of construction tasks and costs. To the authors' knowledge, there have not been studies dedicated to evaluating the effects of time delays in project tasks individually on the completion time of dam-construction projects. Disregarding of uncertainties in dam-construction activities imposes heavy costs on employers and creates long delays in those projects, which may in some cases lead to project failure.

This study evaluates the effects of uncertainty in dam-construction projects. First, the critical path method (CPM) is applied to schedule the activities of dam construction without considering the uncertainty of project activities. Secondly, the effects of uncertainty of dam-construction activities on project completion time are calculated using the project evaluation and review technique (PERT) considering the probability distribution functions of activities within a Monte Carlo simulation (MCS) framework. Also, the uncertainties of construction activities are quantified with risk distribution curves and time-sensitive indicators. The Gelal earth dam and the Khersan 3 concrete dam construction projects in Iran are herein evaluated to assess the performance of the proposed methodology in scheduling dam-construction activities.

Critical Path Method

In CPM, the duration of a project's task or activity is determined based on a deterministic model, which uses the mean time to complete the task or activity. The critical path includes activities whose total float time is equal to zero and no delay is allowed in their completion. Float is the maximum time that an activity can be delayed regardless of the influence of the activity's completion time on the total project completion time. If one adds the time of critical activities together, the time of the critical path is obtained that is equal to the time elapsing from start to finish of the entire project. A critical path or critical activity may not be stable during the project implementation. This may change from one path to another, or from an activity to another, anytime during a project depending on specific conditions.

Program Evaluation and Review Technique

The weighted average time is used for calculating the activities' durations. The main difference between PERT and CPM is in their calculation of activities' durations. PERT uses a weighted average of most likely time, optimistic time, and pessimistic time. CPM uses the mean time. Fig. 1 illustrates the times that are used in both methods.

One of the shortcomings of the PERT method is the difficulty in measuring the optimistic, pessimistic, and most likely times (Littlefield and Randolph 1987). While the Beta probability distribution may be suitable for all activities in PERT, it cannot cover the uncertainty of time required to perform all activities (Grubbs 1962; Mac Crimmon and Ryaveck 1964). Moreover, the most important disadvantage of PERT is that it considers only one critical path. PERT does not consider paths close to the critical path. The importance of this matter is significant when the number of paths close to the critical path is numerous. In this situation, PERT provides a lower estimate of the real time to complete the project (Hendrickson and Au 1989). In other words, if a project network has many close and parallel critical paths, only one critical path is considered while using PERT. If any delay occurs at the time to perform the project's activities, the probability of change in the critical path is high while the time to perform the project increases with the change in the critical path. Thus, one cannot assert with confidence which is the critical path and whether or not there will be changes in the critical path until the end of the project.

The Monte Carlo simulation (MCS) method is herein applied to overcome the shortcomings of PERT. The MCS focuses on the activities that are near the critical path by using probability distributions for the various activities' durations in project scheduling.

Monte Carlo Simulation Method

Monte Carlo simulation generates multiple random input data with which to simulate a system (in this case dam construction) and

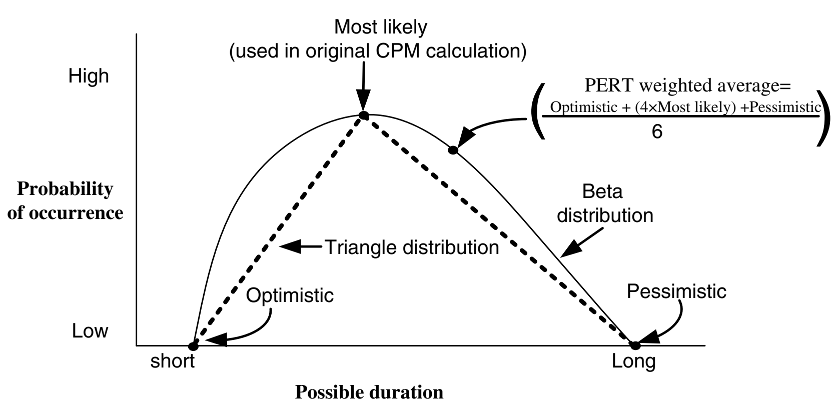

Fig. 1. Beta and triangular distributions' time duration

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calculate multiple random outputs, one for each simulation of the system. The multiple simulation outputs are then statistically analyzed to assess system characteristics.

Indices of Risk Management

This work applies time-sensitive indices for assessing project completion risks. The indices are (1) criticality index (CI), (2) duration sensitivity (DS), (3) cruciality index (CRI), (4) sensitivity schedule index (SSI), and (5) serial/parallel indicator (SP).

Criticality Index

The criticality index measures the importance of activities of projects (VanSlyke 1963; Martin 1965; Fatemi Ghomi and Teimouri 2002). The CI is expressed as a percentage. It shows the ratio of the number of times that an activity is on the critical path of a project to the total number of project simulations with MCS. Activities that have a high CI are more likely to delay the project. The CI is defined by the following equation:

$$\mathrm{CI_j} = \frac{H_\mathrm{j}}{N} \times 100 \quad j = 1, 2, \ldots, n \tag{1}$$

in which j = acting factor; n = number of project activities; H_j = number of times that the jth activity is critical in the MCS; and N = total number of repetitions in MCS method.

Duration Sensitivity Index

The DS of an activity measures the influence that the duration of the activity has on the duration of the total project (*PertMaster*). Activities with a high DS have are more likely to influence the project duration. One calculates the DS from the correlation between the duration of an activity and those of other activities. This correlation is frequently calculated with the Spearman rank correlation (Cho and Yum 1997; *PertMaster*)

$$\rho_j = 1 - \frac{(6 \times \sum_{i=1}^{N} (d_{ij})^2)}{N(N \times N - 1)} \tag{2}$$

in which ρ_j = Spearman rank correlation for the jth activity; i = simulation number of the MSC method; d_{ij} = difference between ranks of the jth activity's duration and the total project duration in the ith simulation; and N = total number of the MSC method simulations.

Pearson's product moment is used for calculating the correlation between two variables (Rodgers and Nicewander 1988). In this method, the correlation is calculated via Eq. (3):

$$r_j = \frac{\frac{\sum_{i=1}^{N}(x_{ij}-\bar{x})(y_i-\bar{y})}{N-1}}{\sqrt{\frac{\sum_{i=1}^{N}(x_{ij}-\bar{x})^2}{N-1}} \times \sqrt{\frac{\sum_{i=1}^{N}(y_i-\bar{y})^2}{N-1}}} \tag{3}$$

where r_j = Pearson product moment correlation for jth activity with the total project duration, expressed as a percentage; x_{ij} = duration of the jth activity in the ith simulation; $\bar{x}_j$ = average duration of the jth activity in all simulations; y_i = project duration of the ith simulation; and $\bar{y}$ = average of project durations in all simulations. In fact, DS can be calculated by correlation between an activity's duration and other activities. So to calculate this correlation, Eq. (3) is used in this study.

Crucially Index

The CRI is used to determine the importance of the duration of an activity on the project duration. A high value of an activity's CRI index signifies that such activity has an influence greater than those of other activities on the duration of the project. The CRI is calculated with the following equation that involves the CRI and DS indices:

$$\mathrm{CRI}_j = \mathrm{DS}_j \times \mathrm{CI}_j \tag{4}$$

The DS of the activities that are not part of the critical path in most of the simulations of the MCS method is small. A small DS maybe the result of a random correlation between the duration of an activity and the duration of the project. Thus, the CRI is designed to show the sensitivity of duration when multiplied by CI (*PertMaster*). Hence, a small DS is weighted by the CRI to focus on activities that have high DS.

Sensitivity Schedule Index

One of the disadvantages in using the CI is that the presence of an activity in all simulations of the MCS method does not imply the importance of that activity for completing a project on time. For example, an activity that has a one-day duration has little influence on the ending time of the project. This may be the case even when an activity has a 100% CRI. To overcome this disadvantage, one can use the SSI.

To identify and rank activities that probably affect the duration and ending date of the project, SSI is calculated with Eq. (5) expressed as a percentage (PMBOK 2004)

$$\mathrm{SSI}_j = \frac{\mathrm{CI}_j \times \sigma_{x_j}}{\sigma_y} \times 100\% \tag{5}$$

where j = activity counter; x_j = duration of the jth activity; σ_{x_j} = standard deviation of the duration of the jth activity in simulation repetitions; y = total duration time of the project; and σ_y = standard deviation of the total project duration for the simulated repetitions.

Combining the CI index and σ_{x_j} causes activities on the critical path in each repetition of the MCS method with influence on project duration to receive special attention. Thus, the value of SSI approaches 100% when there is high relative uncertainty of an activity of the project.

The DS could be used instead of the SSI. One of the benefits of using DS instead of SSI is that the latter is efficient only measuring the influence of an activity's duration on the ending time of the project. In contrast, the DS measures the effect of an activity's duration on the duration of other activities, also.

Serial/Parallel Indicator

The SP indicator which is defined in the range (0, 1) shows whether or not the project follows a serial or parallel network. If SP = 0, all activities are scheduled in parallel, while SP = 1 means that all activities are pursued and the network is totally in a serial order. SP is a topology index more than a sensitivity index (Vanhoucke 2009) and is calculated with the following equation:

$$SP = \begin{cases} 1 & \text{if } n = 1 \\ \frac{m-1}{n-1} & \text{if } n > 1 \end{cases} \tag{6}$$

in which n = number of activities with a non-zero duration (activities that only determine the starting or ending times of key

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milestones are not considered); and m = maximum number of performance activity levels of the project.

Knowledge of the network type plays an important role in the analysis of results from the sensitivity indices. In general, network type is classified as parallel, series, or hybrid, with the latter exhibiting parallel and series components. An index that determines the network type is a topologic index. Knowing the value of the SP index is useful for project analysis at the time of the activities' implementations. The SP index indicates which one of the sensitivity indices out of CI, DS, CRI, and SSI is more effective in project analysis at the time of performing activities. Vanhoucke (2009) states that if the project network is parallel, the CI, DS, SSI, and CRI indices are of most importance. Otherwise, if the project is a series network, the best index for project analysis is the SSI index, which performs well in series networks as well as parallel ones and with hybrids.

The SP indicator influences the accuracy of the forecasts of project completion. Jacob and Kane (2004) reported that delays of noncritical activities decrease the accuracy of forecasts. Therefore, the accuracy of forecasts in parallel activities is lower than those in series ones. In other words, the larger the number of critical activities, the higher will be the accuracy of forecasts.

Case Studies

Two case studies (Gelal earthfill dam and Khersan 3 concrete dam) are used in determining the critical activities and activities that are close to the critical paths in these dam-construction projects in Iran.

Gelal Earthfill Dam

The Gelal earthfill dam will be located in the Chevar area of Ilam province. It will have a height of 70 m and a crest length of 320 m, with a storage volume of 23 million m^3. Its functions would be to provide water for petrochemical production and for supplying potable water to Chevar village. Totally, 110 construction activities are considered for the dam, of which 81 have assigned durations and the remaining 29 depend on the main event activities. Table 1 lists the main tasks, their durations, and prerequisite activities for construction of the dam. In Table 1, major tasks for Gelal earthfill dam construction are divided into 12 activities that are illustrated in the table by A1 to A12 and their descriptions are presented in this table.

Khersan 3 Concrete Dam

Khersan 3 dam will be located in the upper section of the Khersan river in southwestern Iran, near the villages of Talaye and Atash Gahin, and 50 km from Lordegan city. It will feature a concrete double-arch dam with a height of 175 m, reservoir storage volume of 1,581 million m^3, and it is designed to produce 400 mW of electricity with four 100-mW turbines. Its functions would be flood control and to increase electricity production, ecotourism, employment, safety of access roads, and aquaculture in Chahar Mahal in Bakhtiari province. A total of 125 activities are considered in the construction of Khersan 3, whereby 96 activities have assigned durations and the remaining 29 activities depend on the main event activities. Table 2 lists the main construction tasks and their

Table 1. Major Tasks of Gelal Earthfill Dam Construction and Their Indices

Activity	Descriptions	Duration (days)	Prerequisite activities	CI	DS	CRI	SSI
A1	Project start	0	—	100	0	0	0
A2	Site equipping and permanent activities	230	1	65	23	15	29
A3	Temporary diversion system	363	2	93	22	21	43
A4	Water diversion and upstream dam construction	100	3	40	18	7	19
A5	Injection gallery construction	438	2–4	93	34	31	62
A6	Cut off construction	430	5	5	5	0	7
A7	Body and flanks excavation	177	5	88	22	19	65
A8	Filling dam structure	260	7	88	51	45	58
A9	Spillway construction	805	5	47	31	14	21
A10	Precision tool installation	260	8	12	16	2	3
A11	Hydromechanical equipment construction/ installation	500	3	2	3	0	3
A12	Dam inundation and end of project	0	8	—	—	—	—

Table 2. Major Tasks of Khersan3 Dam Construction and Their Indices

Activity	Descriptions	Duration (days)	Prerequisite activities	CI	DS	CRI	SSI
B1	Project start	0		100	0	0	0
B2	Site equipping and permanent activities	547	1	44	19	8	18
B3	Temporary diversion system	791	2	79	18	14	33
B4	Power plant penstock construction	1,035	2–3	13	7	1	6
B5	Water conveyance tunnels construction installation of metal conduits	595	4	27	31	8	12
B6	Power plant building construction	1,310	2–3	2	0	0	0
B7	Power plant equipments construction	945	6	43	22	9	16
B8	Dam structure construction	1,826	2–3	78	37	29	24
B9	Plunge pool construction	792	8	12	10	1	10
B10	Dam inundation and end of project	0	7	—	—	—	—

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durations and their prerequisite activities including 12 activities from B1 to B12 with their descriptions.

Results and Discussions

Project scheduling can be done in two ways: (1) without considering uncertainty using the CPM, and (2) considering uncertainty employing the MCS method. Both methods are used for the scheduling the constructions activities for the Gelal earthfill and Khersan 3 concrete dams.

Scheduling without Consideration of Uncertainty

Gelal Earthfill Dam

Results from scheduling the activities in Gelal earthfill dam construction involve 1,102 days (91.8 months) if uncertainty is not considered for any activity. Fig. 2 shows the summary tasks in Gelal earthfill dam construction that have critical activities. Critical activities are shown in Fig. 2. Scheduling is done for all the activities in which the summary tasks are considered as the main events. According to Fig. 2, the summary tasks of site equipping and permanent activities, as well as spillway construction activities are on the critical path while delay in doing these two activities would cause significant delay completing the construction of Gelal dam.

Khersan 3 Concrete Dam

Results from scheduling the activities of Khersan 3 concrete dam's construction involve 2,352 days (196 months) if uncertainty is not considered for each activity. Fig. 3 shows summary tasks in the construction of the dam that are on the critical path. According to Fig. 3, summary tasks on the critical path include site equipping and permanent activities, temporary diversion system, power plant building construction, and installation of equipment in the power plant. Therefore, delay in any of these four activities would significantly impair the construction of the dam.

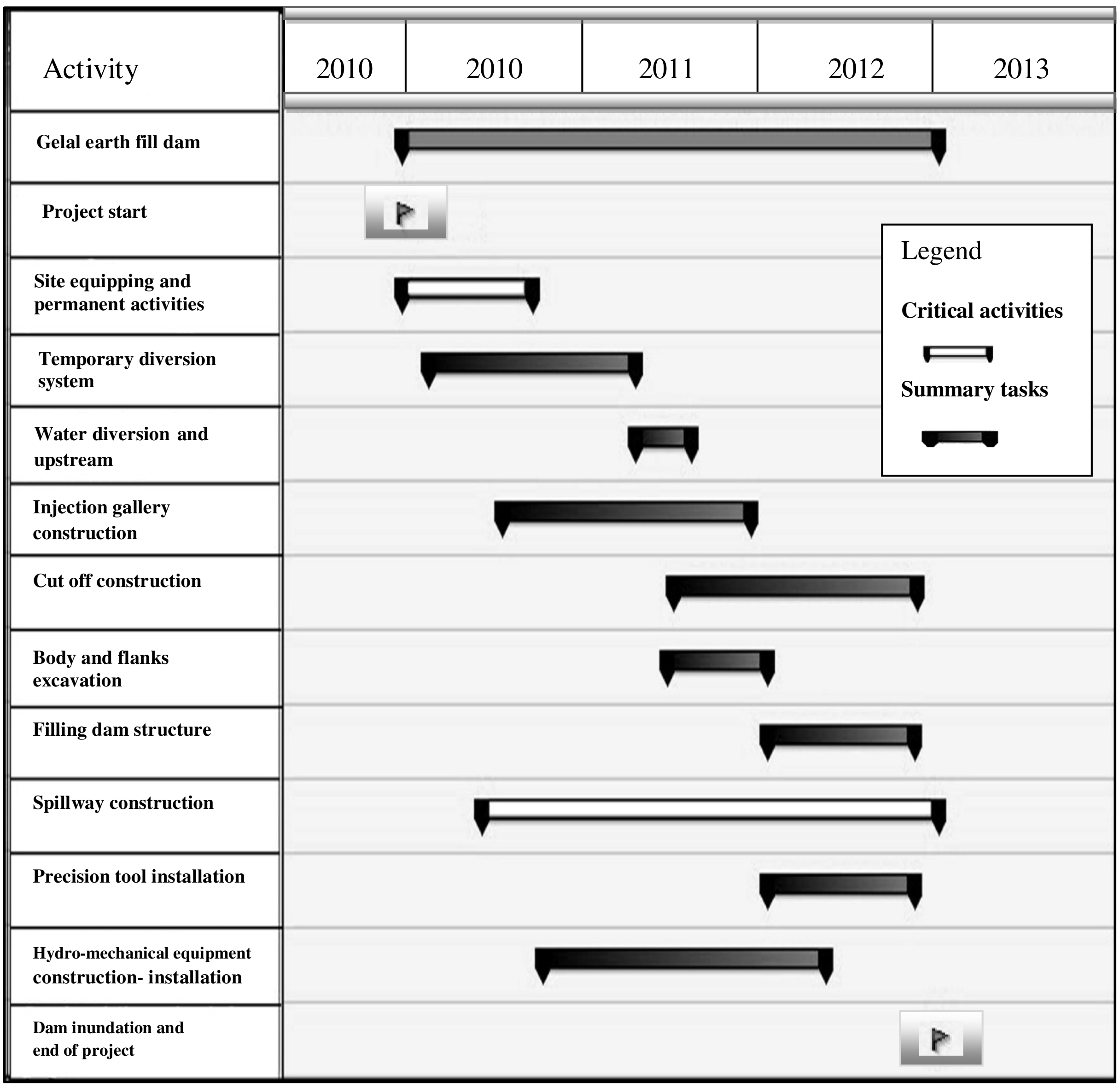

Fig. 2. Summary schedule of the Gelal earthfill dam without uncertainties

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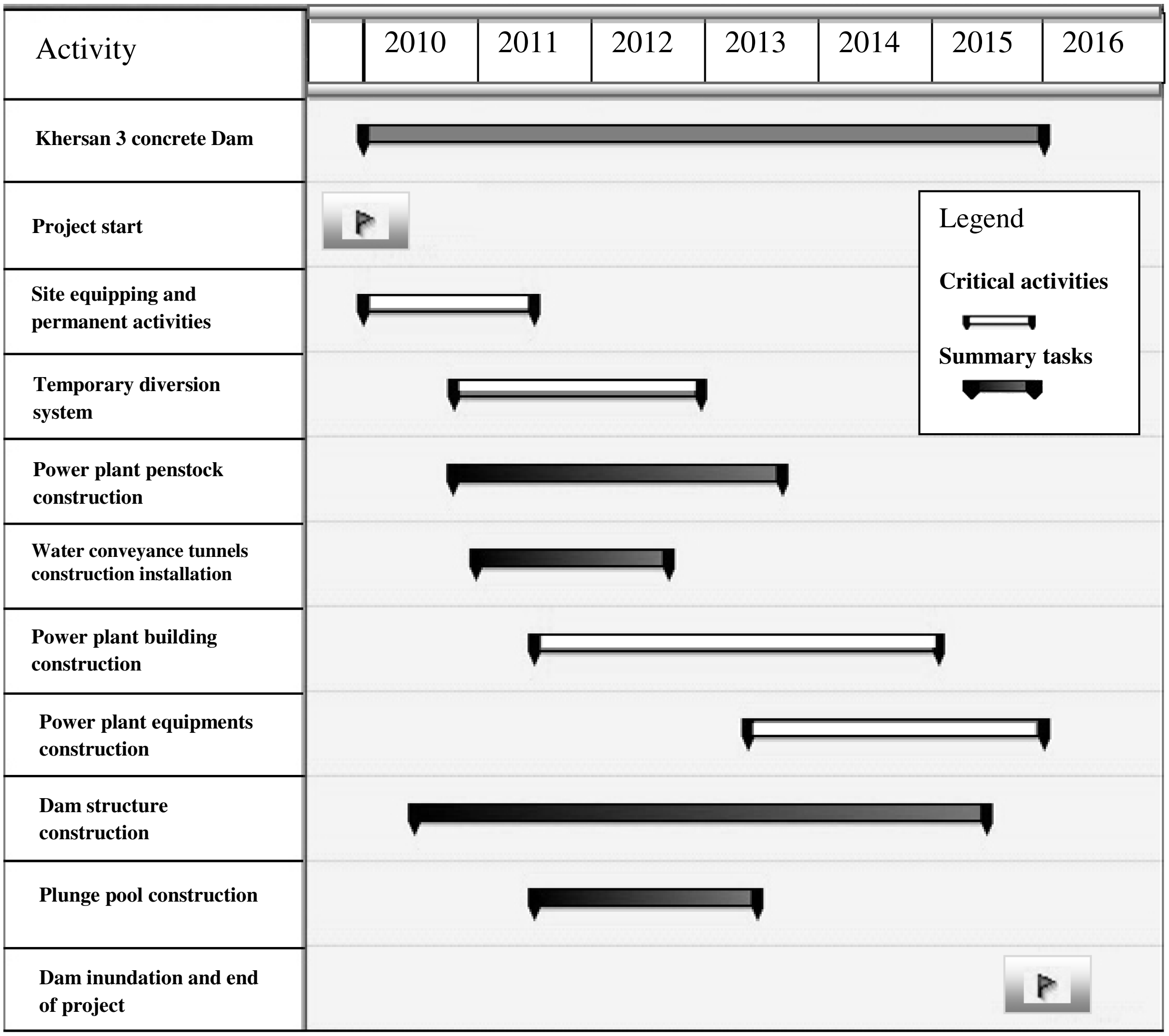

Fig. 3. Summary schedule of Khersan 3 concrete dam without uncertainties

Scheduling with Consideration of Uncertainty

In this section, the project scheduling accounts for the uncertainty of the activities and the calculated results from the risk management's indices of construction activities are discussed. To analyze the project's risk, after preparing the schedule, one enters the risk information and uncertainty in the first level of analysis. The information often enters the program by using probability distribution functions and modeling. A triangular distribution was selected in this work. One must consider the opinion of experts regarding each activity to improve the predictive accuracy of a project's duration. Thus, a questionnaire is prepared for this purpose. Only the main activities including different tasks were included in the questionnaire to reduce time-consuming analysis of all the activities' nuances. These main activities are selected according to the experts' opinion, and they are listed in Table 3, showing the most-likely parameters for triangular distribution of each activity. These parameters are defined in percentages obtained from responses to the questionnaire. In the following, the optimistic, pessimistic, and most likely durations are calculated by multiplying the values from the questionnaire by the initial scheduling time.

Table 3 presents a sample of selected activities for the earthfill and concrete dams. Thereafter, results of the aforementioned analysis were calculated. Also, one has to select a suitable probability distribution function for risk analysis. For simplicity, the triangular distribution was chosen. To estimate the triangular distribution, the opinions of experts were gathered as percentages regarding the uncertainty of the durations in major construction activities, and the obtained average from the experts' opinions were used for modeling the triangular distribution and surveying the uncertainty in performing activities. The viewpoints of about 100 academics and industry experts were gathered through the questionnaire. Subsequently, the calculated results from the diagrams of risk/uncertainty distribution and sensitivity indices for two case studies were estimated. The *PertMaster* software was used for obtaining the sensitivity indices from 10,000 simulations with the MCS method. The construction of earth fill and concrete dams is guided by the analysis of the MCS's results.

Diagrams of Risk/Uncertainty Distribution

Diagrams of risk/uncertainty distribution are commonly used tools in the *PertMaster* software. By using these diagrams, one can answer questions such as the probability of ending an activity on a given date. Diagrams of risk/uncertainty distributions are of different kinds: (1) column distribution of duration, (2) column distribution of ending time, (3) column distribution of beginning time, and

Table 3. Sample of Selected Activities for Gelal Earthfill Dam and Khersan 3 Concrete Dam

		Percentage changes on a preset schedule					
		Decrease (<100)			Increase (>100)		
Number	Activity	Minimum	Average	Maximum	Minimum	Average	Maximum
1	Site equipping and access roads	80	88	95	105	113.75	125
2	Temporary diversion system and stilling basin construction	85	89	95	110	125	140
3	Excavation	85	91	95	105	123.13	150
4	Reinforcement	85	92	99	110	117.5	130
5	Foundation	85	90	95	110	119.38	130
6	Concrete	80	91	95	110	125	140
7	Upstream and downstream cofferdam	85	91	95	110	118.75	130
9	Excavation	85	91	95	105	114.38	120
10	Filling	85	90	95	110	116.25	125
11	Reinforcement	85	92	99	110	115.63	120
12	Foundation	85	92	99	110	116.88	125
13	Concrete	85	91	95	115	120	135
14	Spillway and stilling basin (earthfill dam)	90	93	99	120	130	140
15	Excavation	85	93	99	115	126.25	140
16	Filling	90	92	95	105	118.75	130
17	Reinforcement	90	93	99	110	121.25	130
18	Foundation	85	92	99	115	120.63	135
19	Concrete	90	92	95	110	120	130
20	Power plant penstock construction	85	94	99	125	134.38	150
21	Excavation	85	92	99	120	123.75	140
22	Reinforcement	85	92	99	115	124.38	140
23	Foundation	90	93	95	115	123.13	150
24	Body dam and cut of constructions (earthfill dam)	90	94	95	115	126.88	155
25	Excavation	85	93	99	125	134.38	150
26	Filling	90	93	95	120	126.25	140
27	Reinforcement	90	92	99	120	128.75	150
28	Foundation	90	93	95	115	131.88	150
29	Concrete	90	93	95	110	131.88	160
30	Body dam, cut of and spillway constructions (concert dam)	85	91	99	135	150	180
31	Excavation	85	90	99	125	137.5	150
32	Reinforcement	80	90	99	130	140.63	150
33	Foundation	85	92	99	120	129.38	140
34	Concrete	85	92	95	120	126.88	135
35	Hydromechanical equipment construction/installation	80	90	95	115	127.5	135
36	Precision tool installation	85	93	99	120	139.38	160

(4) float time distribution. This work reports the column diagram of duration distribution because it is more important than other risk/uncertainty distribution diagrams in project construction.

Gelal Earthfill Dam

Fig. 4 shows the column distribution of durations in the Gelal earthfill dam construction where it is seen that the project will end most likely in 1,102 days with a probability of 65%. In other words, 650 out of 1,000 project simulations were completed earlier than the expected execution time. Therefore, the project may fail to end within the determined time with a probability of 35%. The column diagram of duration shows that the construction of Gelal earthfill dam is expected to last most likely for a minimum 999 days and a maximum 1,235 days.

Khersan 3 Concrete Dam

Fig. 5 shows the column distribution of durations in the construction of the Khersan 3 concrete dam. According to the column diagram of durations, the construction of Khersan 3 concrete dam is most likely to take a minimum 2,193 days and a maximum of 2,506 days and the cause of the difference between durations in Fig. 5 and Fig. 3 arises from considering uncertainty in Fig. 5. It is seen in Fig. 5 that the project most likely will end in 2,352 days with a probability of 51%. Thus, the project may fail to end within the determined time with a probability of 49%. The results from risk diagrams show much uncertainty in completing the project activities of the construction of earthfill and concrete dams. More-sensitive activities must be considered to resolve this problem.

Time Sensitivity Indices

Gelal Earthfill Dam

SP Indicator

Among 110 activities necessary to perform, 81 activities were assigned durations, and among these, 29 major activities were considered for constructing the Gelal earthfill dam. The SP indicator for the Gelal earthfill dam is $SP = (29 - 1)/(81 - 1) = 0.3$.

The SP indicator is close to zero for construction of the Gelal earthfill dam and this shows the closeness of the activities' network to a parallel activity network structure for this dam.

CI, DS, CRI, and SSI Indices

Table 1 lists the results from the *PertMaster* software for the time sensitivity indices CI, DS, CRI, and SSI and all the activities of the Gelal earthfill dam. Analysis of time indices requires the determination of a suitable sensitivity threshold at the first step. Corrective

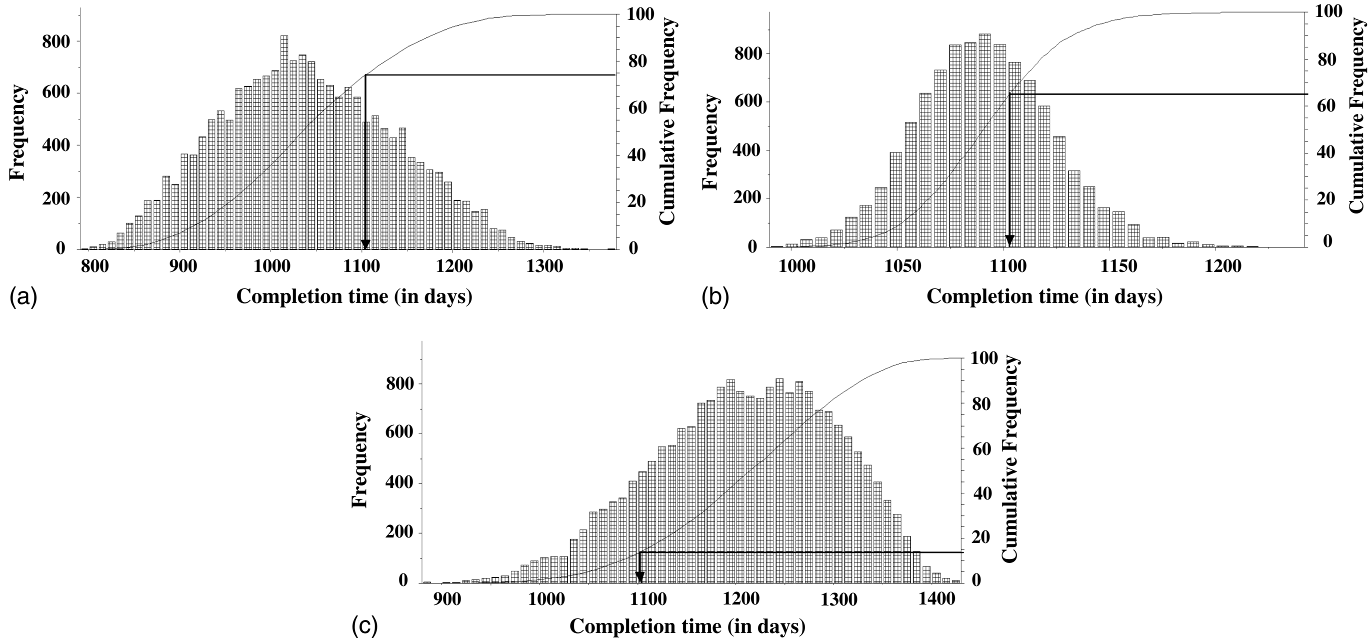

Fig. 4. Column distribution of (a) optimistic; (b) most likely; (c) pessimistic duration for Gelal earthfill dam construction

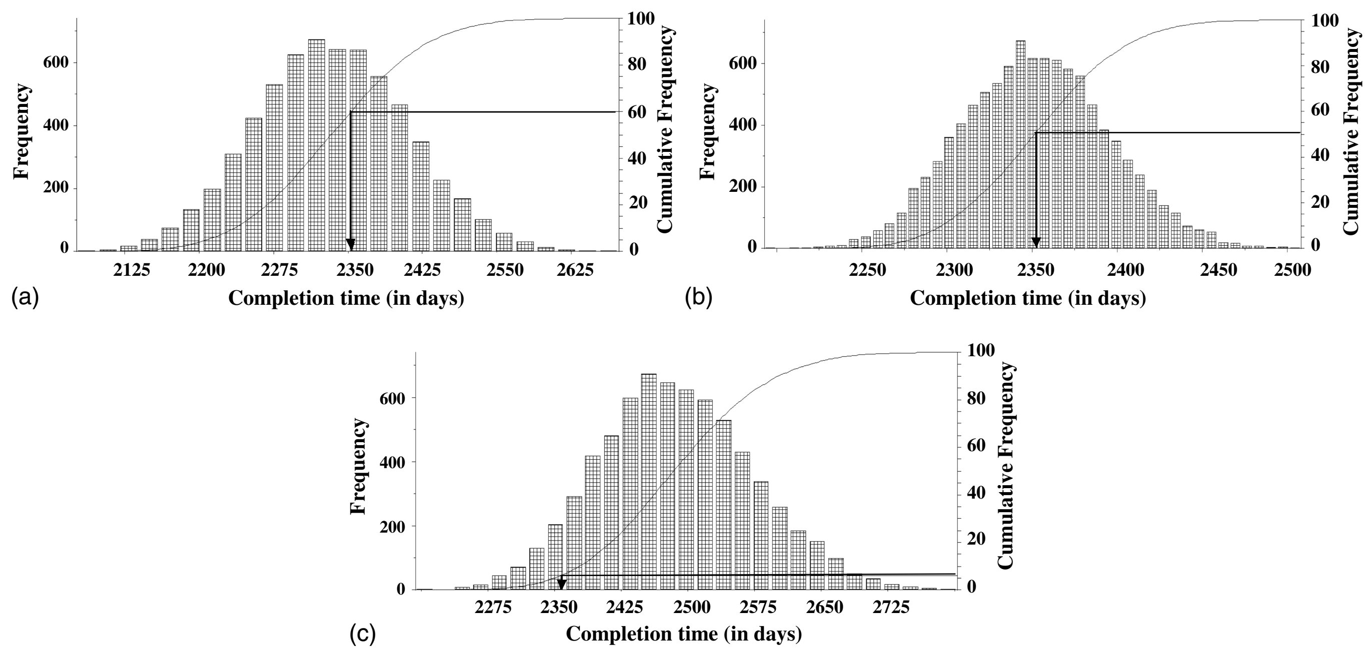

Fig. 5. Column distribution of (a) optimistic; (b) most likely; (c) pessimistic duration for Khersan 3 concrete dam

actions must be taken for an activity if its time sensitivity index is higher than the sensitivity threshold. The average sensitivity value is used for summary tasks.

It is observed in Table 1 that the project starting activity with $\mathrm{CI} = 100\%$ and $\mathrm{DS} = 0\%$ is a milestone activity of the project. Other main tasks include site equipping and permanent activities, temporary diversion system, water diversion, and constructing the upstream dam, injecting gallery construction, body and flank excavation, and filling the dam structure as well as spillway construction that have high temporal sensitivity indices. Despite the predefined scheduling of Gelal earthfill dam's construction in which only the tasks of site equipping and permanent activities as well as spillway construction are on the critical path, the activities of temporary diversion system, body excavation at the base and flanks have high temporal sensitivity in the execution time. The dashed lines in the last row of table do not imply zero, because the project are at the end and there is not any activity at project's end point so indices aren't estimated. Existing uncertainty in dam execution is an undeniable fact which can be increased by ignoring the critical activities and eventually delaying the project. The average sensitivity threshold index should be used to highlight the increasing importance of the summary tasks with increasing values of

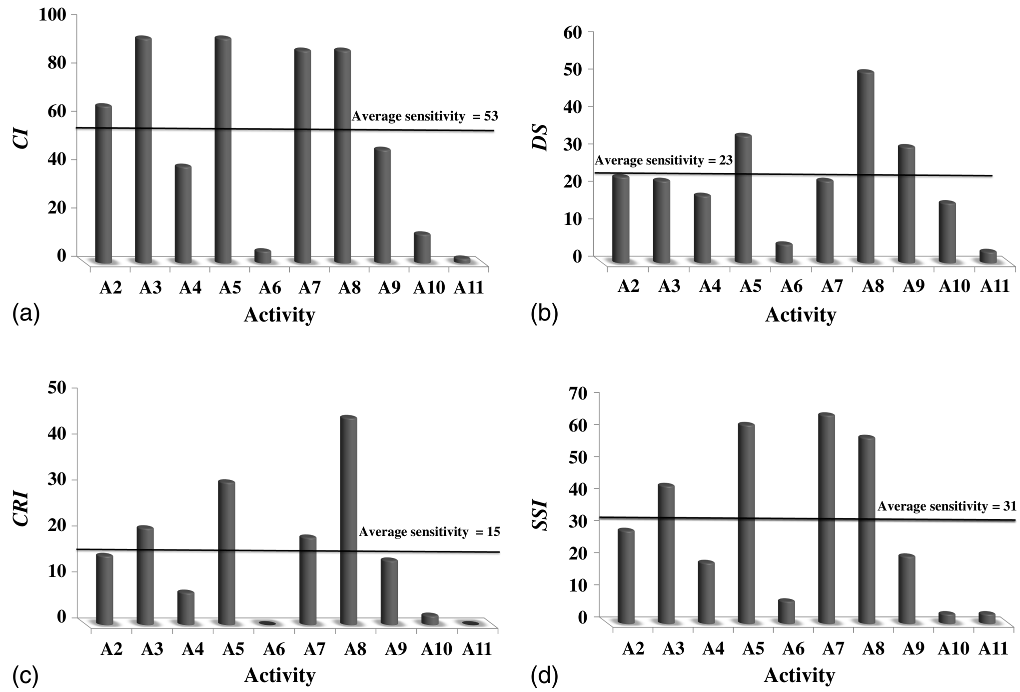

Fig. 6. Average sensitivity graphs of (a) CI index; (b) DS index; (c) CRI index; (d) SSI index for Gelal earthfill dam

the sensitivity indices. Diagrams of the CI, DS, CRI, and SSI indices and the average sensitivity threshold for summary tasks of the Gelal earthfill dam are depicted in Fig. 6.

Fig. 6(a) establishes that summary tasks of temporary diversion system, injection gallery construction, body and flanks excavation, as well as filling dam structure have the highest priorities. Water diversion and construction of upstream dam, as well as spillway construction, have the second-highest priorities of the requirements of corrective actions, and these activities receive more attention compared to other activities. The CIs of these activities are respectively 65, 93, 88, 93, and 88% which is greater than the average CI of 53%. The summary tasks of water diversion and constructing upstream dam as well as spillway construction have CI values equal to 40 and 47%, respectively, and are slightly below the average value of the CI, and, hence, are placed in the second priority rankings.

Fig. 6(b) shows that summary tasks of site equipping and permanent activities, injection gallery construction, filling dam structure, and spillway construction have DS values higher than the value of the average DS index of 23%, with corresponding DS index values equal to 23, 34, 51, and 31%, respectively. The summary tasks of temporary diversion system, water diversion and constructing upstream dam, and excavation of body and flanks have values equal to 22, 18, and 22%, which are lower than the average DS index value, thus needing a lower priority ranking. Fig. 6(c) shows the CRI value for the summary tasks of Gelal earthfill dam construction project that result from the multiplication of CI and DS indices. The average value of CRI is equal to 15%. On the other hand, the summary tasks of temporary diversion system, injecting gallery construction, body and flanks excavation, and filling the dam structure have a higher CRI than the average CRI value, equal to 21, 31, 19, and 45%, and are assigned the highest priority ranking according to the CRI. The summary tasks of site equipping and permanent activities as well as spillway construction have a CRI of 15 and 14 respectively, which is nearly the same as the average value of CRI, and, hence, they are assigned a second priority ranking.

Fig. 6(d) shows SSI for summary tasks of the Gelal earthfill dam project and the average SSI value equal to 31%. The summary tasks of temporary diversion system, injection gallery construction, body and flanks excavation, and filling dam structure have SSI values equal to 43, 62, 65, and 58%, respectively. Based on these above-average values of SSI, they are assigned the highest priority ranking, whereas the summary tasks of site equipping and permanent activities, and spillway construction are assigned the second priority ranking.

It is seen in Fig. 6 that the spillway construction activity with a long duration is located on the critical path. However, the CI, CRI, and SSI are lower than the average sensitivity. Therefore, neglecting the uncertainties in these activities may cause a change in the critical path activities and it may cause a delay in the completion of the dam.

All the sensitive activities for the Gelal earthfill dam construction with regard to calculated indices are listed in Table 4. These are the activities whose uncertainties exceed those of others, and ignoring this finding can cause project time overruns.

Khersan 3 Concrete Dam

SP Indicator

According to the definition of SP, 96 activities were assigned durations and 10 major activities are considered for the uncertainty analysis in the construction of the Khersan 3 concrete dam. Thus, the SP indicator for Khersan 3 concrete dam is equal to $SP = 10 - 1/96 - 1 = 0.1$

The SP index is nearly zero for construction of Khersan 3 concrete dam, and, therefore, the network structure of the two construction projects of earthfill and concrete dams are respectively 0.3 and

Table 4. Most Sensitive Activities for Gelal Earthfill Dam Construction

Major tasks	Tasks
Site equipping and permanent activities	Initial site equipping Supply of required equipment and machines Complementary site equipping Temporary diversion system Diversion tunnels and outlet system
Temporary diversion system	Portals diversion tunnel Outlet system
Water diversion and upstream construction	Water diversion Upstream's filling and excavation Injection gallery Foundation and injection gallery in middle Injection gallery's lining in the middle Injection gallery's lining in the middle
Body excavation	Middle excavation at upstream and downstream Excavation of left and right base
Filling dam structure	Cleaning Delivery of embankment Filtering
Spillway construction	Concrete

0.1, showing that the network structures for the two dam projects are close to a parallel structure.

CI, DS, CRI, and SSI Indices

Table 2 lists the calculated results of temporal sensitivity indices of CI, DS, CRI, and SSI for the major tasks of the Khersan 3 concrete dam construction.

Fig. 7 graphs the CI, DS, CRI, and SSI indices and the average sensitivity threshold for the major tasks of Khersan 3 concrete dam. Based on Fig. 7(a), the summary tasks of site equipping and permanent activities, temporary diversion system, power plant equipment construction, and dam structure construction have CI values equal to 44, 79, 43, and 78% respectively, which are higher than the average CI value of 37%. Therefore, they are categorized as a first priority. Water conveyance tunnels construction, and installation of metal conduits, power plant penstock construction, and plunge pool construction respectively have CI equal to 27, 15 and 12% and are in the second priority of consideration. They should receive more attention than other activities like power plant buildings with CI values of near zero.

It is seen in Fig. 7(b) that the summary tasks of site equipping and permanent activities, temporary diversion system, water conveyance tunnels construction, and installation of metal conduits, power plant equipment construction, and dam structure construction respectively have DS index values equal to 19, 18, 31, 22, and 37%, which are higher than the average DS index value of 18%. Plunge pool construction with a 12% DS value is in the second priority ranking, higher than those of other activities including power plant construction and power plant building with 6 and 0% DS values, respectively.

Fig. 7(c) shows that the average value of the CRI index is equal to 9%. On the other hand, the summary tasks of temporary diversion system, power plant equipment construction, and dam structure construction, respectively, with CRI values of 14, 9, and 29% are higher than the average value of CRI and are assigned the highest priority ranking. Summary tasks of equipping and permanent activities, and water conveyance tunnels construction and installation of metal conduits, each have CRI values equal to 8%, which are nearly the same as the average of CRI and, therefore, they are in the second priority ranking in terms of their CRI index.

Fig. 7(d) graphs the values of the SSI index for summary tasks of the Khersan 3 concrete dam project, with an average SSI index equal to 15%. Fig. 7(d) shows that the summary tasks of site equipping and permanent activities, temporary diversion system, power plant equipment construction, and dam structure construction have respective SSI index values equal to 18, 33, 16, and 24%, which are higher than the average SSI value. Hence, they are assigned the highest priority ranking. The summary tasks of water conveyance tunnels construction, installation of metal conduits, and plunge pool construction are in the second priority ranking that need

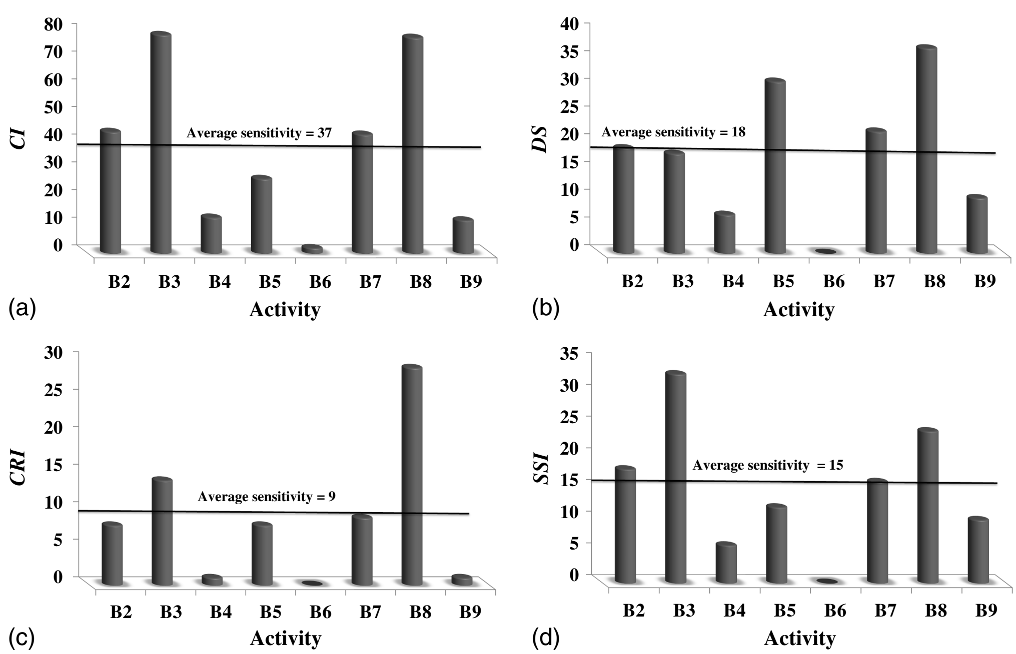

Fig. 7. Average sensitivity graphs of (a) CI index; (b) DS index; (c) CRI index; (d) SSI index for Khersan 3 concrete dam

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Table 5. Most Sensitive Activities for Khersan 3 Concrete Dam Construction

Major tasks	Tasks
Site equipping and permanent activities	Initial site equipping Complementary site equipping Access roads to power plant Access road to tunnel Access road to dam crest
Temporary diversion system	Site equipping Diversion tunnel Flow conveyance to tunnel
Power plant equipments	Power plant equipping installation Dam structure construction

special attention compared to other activities including power plant penstock construction and power plant building construction with 6 and 0% SSI values, respectively, which, in turn, have higher priority than water conveyance tunnels construction and installation of metal conduits, and plunge pool construction.

The values depicted in Figs. 6 and 7 were calculated with the *PertMaster* software. The average sensitivity value was computed as the arithmetic mean of the sensitivity values of all the major activities in these two figures.

The most sensitive activities for Khersan 3 concrete dam construction are listed in Table 5.

Concluding Remarks

This study addressed the construction activities of Iran's Gelal earthfill dam and Khersan3 concrete dam. First of all, major activities were analyzed without considering uncertainty in their time duration, scheduling, along with critical activities for both the case studies of dam construction. Then, the scheduling was analyzed considering the uncertainties in activities by the *PertMaster* software and time sensitivity indices were obtained for each one of the dams. Subsequently, the average sensitivity values of threshold level were chosen for analysis. The results obtained from the analysis of time sensitivity indices for Gelal earthfill dam and Khersan 3 concrete dam construction were presented.

The following conclusions can be made from results of this study:

1. The calculated results of the SP index for earthfill and concrete dam construction project case studies indicate that the two networks have a nearly parallel structure. The parallel structure shows the low accuracy of forecasts at the time of under taking the project. Therefore, managers who are responsible for the activities of constructing the dams must be attentive in this respect.
2. The probability of completing the earthfill dam and concrete dam project case studies are respectively 65 and 51% if uncertainty is considered in 29 and 10 of the major activities, respectively.
3. The tasks of site equipping and permanent activities, temporary diversion system, injection gallery construction, body and flanks excavation, filling dam structure, and the spillway construction in an earthfill dam have more importance than the tasks of water diversion and construction of the upstream dam, cutoff construction, precision tool installation and hydromechanical equipment construction/installation. Therefore, attention to the timely completion of the activities with a high temporal sensitivity index can prevent project delays and escalation in project costs, and
4. The tasks of temporary diversion system and dam structure construction are more sensitivity than the tasks of power plant equipment construction and site equipping and permanent activities in the concrete dam case study. Hence, these two activities have high importance in the project execution time.

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