

Dynamic Cooperative Model for Ranking Construction Risks using Monte Carlo Simulation

Amr Mahmoud, Ahmed Elhakeem, Ahmed Elyamany

Abstract: Construction projects suffer from diverse uncertainties that hinder the key objectives' achievement. These uncertainties represent risks that may appear through the project life cycle. This paper introduces a quantitative model to estimate and rank risks dynamically during the risk planning phase. Such ranking would help decision-makers appropriately respond to and/or control construction risks. The model provides proper risk contingency reserves for both project time and cost that meet decision-makers' selected confidence levels using Monte Carlo Simulation (MCS). In order to quantify the project uncertainty, severities of residual risks are determined and allocated at the project's activities-level using a planning/scheduling spreadsheet model and a MCS tool suitable for spreadsheets. The model is able to calculate the contribution of each risk from the determined contingency at both the project level for both the time and cost at the decision-maker confidence level. The model represents a direct implementation for a Risk Planning Contingency Model (RPCM); which involves four modules as follows: (1) Risk Register (RR), (2) Risk Allocator (RA), (3) Risk Simulator (RS), and (4) Contingency Calculator (CC). These modules are hosted in a critical path model scheduling spreadsheet to facilitate risk management. In addition, a simulation engine add-in is used for analyzing the probability distribution for the project time and cost outcomes. In order to verify the proposed model, the process and analysis have been applied to a case study project. The results show that the RPCM is capable to rank and estimate the residual risks in an easy, fast, and effective way.

Keywords: Contingency Reserve, Monte Carlo Simulation, Risk Ranking, and Quantitative risk analysis

I. INTRODUCTION

Construction industry projects have high degrees of uncertainties that could dissuade the achievement of the project objectives. The majority of construction projects exceeds deadlines and target budgets [1]. In 2008, [2] attributed the reasons for time and cost overruns in coping with risks in the planning phase [2]. According to the PMBOK Guide, risk "is an uncertain event or condition that, if it occurs, has a positive or negative effect on a project's objectives" [3]. By definition, a risk is administrated by its probability of occurrence and its impact on project objectives.

Construction participants add contingency reserves to

cover unpredictable risks that may incur during construction. These contingency reserves are defined by PMBOK Guide as the amount of funds, budget or time needed above the estimate to reduce the risk of overruns of project objectives [3]. The contingency reserve tries to reduce the risk impact that appears during construction. However, the risk could have a positive and negative impact on the project. This research investigates the negative risk as it is crucial for project success. Generally, the process in risk management is divided into two main phases; planning and construction. The planning phase includes identifying risk events, performing qualitative risk analysis, and quantitative risk analysis and plan risk responses. On the other hand, the construction phase includes updating risk events and monitoring the project objectives and allocated reserves. Although the main output of risk planning in current practice and research is the determination of an appropriate contingency reserve, for cost and/or time, it is at equal importance to know the reserve share for each risk, which is not addressed yet. Ranking residual risks and determining the contingency reserve for each risk individually would support the best risk response action and better control for risks during construction. One of the techniques that have been used by the project managers for risk analysis is the Monte Carlo Simulation (MCS) which is the most widely used method for risk analysis [4], [5]. MCS generates a random sample of values to represent the required variable, whose uncertainty to be quantified. The input parameters are usually represented by a probability distribution. MCS simulates the whole system to generate the statistical distribution of the output. The output is represented as a probability distribution function of the whole system based on the number of iterations. Within the project management context, the derived probability distribution could represent the total project cost and/or time. A stochastic allocation of project allowances method to estimate the time contingency using MCS with the aid of a Critical Path Method (CPM) for control purposes is purposed by [6]. A framework was developed to allocate cost contingency for a hydropower construction project at the work package level. The contingency was estimated due to the impact of risk on the line item through different classes based on scope definition. The total effect of ranges was simulated through the Monte Carlo Simulation (MCS). The contingency founded to be 25.66% compared to the actual cost overrun for this study which was 26.59% [7].

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* Correspondence Author

Amr Mahmoud, Graduate Student, Construction and Building Engineering Department, Arab Academy for Science, Technology & Maritime Transport, Cairo, Egypt. Email: amr.mahmoud92@aast.edu

Ahmed Elhakeem, Associate Professor, Construction and Building Engineering Department, Arab Academy for Science, Technology & Maritime Transport, Cairo, Egypt. Email: aelhakeem@aast.edu

Ahmed Elyamany, Associate Professor, Construction Engineering Department, Zagazig University, (Currently at The British University in Egypt). E-mail: drahmedelyamany@yahoo.com

In 2017, [8] Introduced a probabilistic model to estimate project cost contingency through qualitative risk analysis and stochastic quantitative analysis using Monte Carlo Method. The results showed two different coverage levels for one contingency amount which means it is important to choose the type of distribution to avoid misleading results. A multiple risk-levels (MRL) model is proposed to tackle the duration of risk during the construction project, which use the Risk-based Critical Path Scheduling Method (R-CPSM) to calculate the duration of the project considering six categories, including environmental factors and the “5 Ms” of construction management; Man, Machine, Material, Method and Money [9]. In 2019, [10] proposed a methodology for estimating time and cost contingency using MCS. The methodology allows the allocation of risk contingencies for multidisciplinary works or activities quantifying time and cost contingency budget. In conclusion, most of the previous researches focused on estimating the contingency reserve at the project level, with very few focusing on ranking and prioritizing the residual risks. The objective of this research is to introduce a Risk Planning Contingency Model (RPCM) to estimate contingency reserve and rank the residual risks relative to the decision-maker’ accepted confidence level for the appropriate risk response selection.

II. RISK PLANNING CONTINGENCY MODEL (RPCM)

In order to build the RPCM, a CPM is modeled to define the project network in terms of activities and logical relationships. The CPM is used as a scheduling engine to reach the project's total time. In addition, it accumulates activities costs for calculating the project total cost. This is done in the (Risk-free state) where there is no risk identified yet. To proceed with the planning process, the project network is defined first in terms of activities, logical relationship, Risk-Free State Time (RFST), and Risk-Free State Cost (RFSC) at the activity level. An example network, shown in Fig.1 and is used hereafter to illustrate the use of the RPCM. Fig.1 shows the critical path in red shaded color based on logic and time. The related information about this example including “Activity ID and name”, “Predecessors”, “RFST” and “RFSC” are presented as a part of the (Risk Allocator) as shown in Fig.4.a

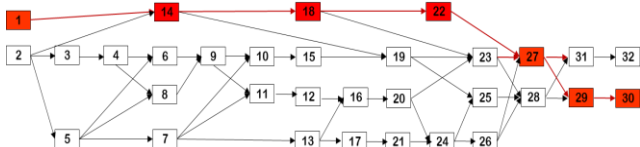


Fig. 1. Implementation example

In order to determine the impacted project time and cost (Risk-State), risks need to be defined and then allocated at the activity-level. Therefore, a risk register is needed for defining risks, their probabilities, and their impacts on the (Risk-State). A simulation engine is used to simulate those impacts with the aid of an add-in program. The same CPM model considers the impacted time and cost due to risk uncertainty (Risk-State) and determines the impacted project time and cost. The RPCM has four main functions to supports the risk planning phase as shown in Fig. 2:

(1) Handling risk information and risk tolerance via the Risk Register (RR).

- (2) Allocating the risk on the project activities via the Risk Allocator (RA).
- (3) Simulating the impacts of risks at the project-level via the Risk Simulator (RS) for the impacted project time and cost (Risk-State).
- (4) Calculating the proper contingency reserves for time and cost at the project level via Contingency Calculator (CC)

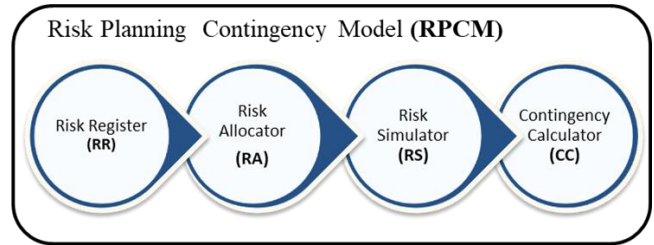


Fig. 2. Risk Planning Contingency Model (RPCM)

The ultimate target of the RPCM model is to reach the project contingency reserves and to rank the residual risks according to its contribution to contingency and the confidence level selected by the decision-maker. Details regarding these processes are discussed using the example to clarify the use of the RPCM in the following subsections.

A. Risk Register (RR)

The Risk Register (RR) is the documentation mechanism responsible for registering possible risks that may happen during construction. The information covers risk ID, probability of occurrence, and impacts on both time and cost as shown in Fig. 3 The probabilities of risks can take the form of values and/or distributions, however, the impacts on either time or cost are presented in the form of custom or known distributions. The custom distributions are based on experts’ opinions. The distributions for the probabilities and impacts are user inputs that can be facilitated using spreadsheet simulation add-ins. @Risk from Palisade Incorporation [11] is used in this paper as the simulation tool to evaluate different possible scenarios. The (RR) follows the risk-driven approach, where the root cause of any risk is identified and mapped to the activities for both time and cost [12], [13]. As shown in Fig. 2, the RR module calculates the risks’ severities for both time (S_t) and cost (S_c), simply by using the multiplication rule; (Severity = Probabilities * Impact) [3].

Risk ID	Probability (p)	Impact (It)	Impact (Ic)	$S_t (p \cdot I_t)$	$S_c (p \cdot I_c)$	
1	r_1	=RiskTriang(0.3,0.5,0.7)	=RiskTriang(0.1,0.2,0.4)	=RiskTriang(0.2,0.4,0.8)	0.12	0.23
2	r_2	=RiskTriang(0.3,0.3,0.5)	=RiskTriang(0.1,0.2,0.4)	=RiskTriang(0.2,0.4,0.8)	0.06	0.12
4	r_4	=RiskTriang(0.5,0.7,0.9)	=RiskTriang(0.2,0.4,0.8)	=RiskTriang(0.1,0.2,0.4)	0.33	0.18
5	r_5	=RiskTriang(0.3,0.5,0.7)	=RiskTriang(0.2,0.4,0.8)	-	0.12	0.09
6	r_6	=RiskTriang(0.3,0.5,0.7)	=RiskTriang(0.1,0.2,0.4)	=RiskTriang(0.1,0.2,0.4)	0.12	0.12
7	r_7	=RiskTriang(0.3,0.5,0.7)	=RiskTriang(0.1,0.2,0.4)	=RiskTriang(0.1,0.2,0.4)	0.06	0.06
8	r_8	=RiskTriang(0.3,0.5,0.7)	-	=RiskTriang(0.1,0.2,0.4)	0.00	0.12
9	r_9	=RiskTriang(0.3,0.5,0.7)	=RiskTriang(0.1,0.2,0.4)	-	0.06	0.00
10	r_{10}	0.27	=RiskTriang(0.1,0.2,0.4)	=RiskTriang(0.2,0.4,0.8)	0.00	0.12

Fig. 3. Risk Register (RR)

B. The Risk Allocator (RA)

The Risk Allocator (RA) is a complementary part of the CPM model where risks can be allocated on projects' activities before proceeding to CPM calculations. The (RA) allows the user to allocate "Risks", as shown in Fig.4.b. The model is limited for illustrated purposes to three risks allocated for each activity. However, this can be easily adapted for more risks. The model calculates the percentage of additional time, and cost by accumulating the severities of allocated risks. For example, in Fig. 4.b two risks "r2" and "r3" are allocated to "Activity E" which has a RFST equal to 25 days. The accumulated severities with respect to time for these two risks are $0.06 + 0.33 = 0.39$ (39 %). As shown in Fig. 4. b, this value represents the additional percentage time for "Activity E"

which equals $25 \times 0.39 = 9.75$ days to be added to the original time for Activity E which resulting in $(34.75 \approx 35)$ days as impacted time. The project time at (Risk-free state) and the impacted time at (Risk state) are 296 and 321 days, respectively. Similarly, for project cost, the (Risk-free state) cost is \$485,000 while the impacted cost equals to \$523,764. With the dynamic and transparent nature of the model, any change in the values of the probabilities and impacts of the allocated risks, as per Fig.2 will be directly reflected in terms of Project impacted time and cost. The CPM model as such represents a suitable platform for simulation where time and cost can be tracked. The Risk Simulator (RS) module simulates the project time and cost with the possible changes of risks' probabilities and impacts.

Project Risk-Free State Cost (RFSC _p)											Critical Path Method (CPM) Calculations				Impacted cost			S523,764			
Project Risk-Free State Time (RFST _p)											296				Impacted Time			321			
ID	Activity Name	Predecessors				Risk-free state time	Risk-free state cost	Early Start	Early Finish	Late Start	Late Finish	Total Float	Risks			Impacted time		Impacted cost			
		P1	P2	P3	P4								RFST	RFSC	ES	EF	LS	LF	TF	1	2
1	A					30	\$12,000	0	30	0	30	0	r ₁			12%	34	23%	\$14,800		
2	B					25	\$11,000	0	25	5	30	5	r ₁			12%	28	23%	\$13,567		
3	C	2				23	\$10,000	25	48	30	53	5				0%	23	0%	\$10,000		
4	D	3				20	\$9,000	48	68	53	73	5	r ₂	r ₃		39%	28	29%	\$11,590		
5	E	2				25	\$12,000	25	50	48	73	23	r ₂	r ₃		39%	35	29%	\$15,453		
6	F	4				25	\$12,000	68	93	73	98	5	r ₄			12%	28	0%	\$12,000		
7	G	5				25	\$12,000	50	75	93	118	43	r ₄			12%	28	0%	\$12,000		
8	H	4	5			20	\$15,000	68	88	78	98	10	r ₄			12%	22	0%	\$15,000		
9	I	6	8			20	\$15,000	93	113	98	118	5				0%	20	0%	\$15,000		
10	J	9				20	\$15,000	113	133	123	143	10				0%	20	0%	\$15,000		
11	k	9	7			25	\$13,000	113	138	118	143	5				0%	25	0%	\$13,000		
12	L	10	11			20	\$10,000	138	158	143	163	5	r ₅			12%	22	12%	\$11,167		
13	M	7				25	\$14,000	75	100	138	163	63	r ₅			12%	28	12%	\$15,633		
14	N	1	2			72	\$40,000	30	102	30	102	0	r ₂			6%	76	12%	\$44,978		
15	O	10				20	\$12,000	133	153	150	170	17	r ₅			12%	22	12%	\$13,400		
16	P	12	13			20	\$13,000	158	178	170	190	12				0%	20	0%	\$13,000		
17	Q	12	13			27	\$15,000	158	185	163	190	5				0%	27	0%	\$15,000		
18	R	14				72	\$50,000	102	174	102	174	0	r ₃	r ₅	r ₆	18%	85	6%	\$53,111		
19	S	14	15			15	\$8,000	153	168	215	230	62	r ₆			6%	16	6%	\$8,498		
20	T	16				20	\$11,000	178	198	190	210	12	r ₆			6%	21	6%	\$11,684		
21	U	17				20	\$14,000	185	205	190	210	5	r ₆			6%	21	6%	\$14,871		
22	V	18				72	\$60,000	174	246	174	246	0	r ₇	r ₈		6%	76	12%	\$67,000		
23	W	18	19			15	\$12,000	174	189	231	246	57	r ₇	r ₈		6%	76	12%	\$13,400		
24	X	20	21			20	\$13,000	205	225	210	230	5				0%	20	0%	\$13,000		
25	Y	19	24			16	\$9,000	225	241	230	246	5	r ₇	r ₈		6%	17	12%	\$10,050		
26	Z	24				10	\$6,000	225	235	236	246	11	r ₇	r ₈		6%	11	12%	\$6,700		
27	AA	22	23	26		15	\$7,000	246	261	246	261	0				0%	15	0%	\$7,000		
28	AB	23	25	26		15	\$7,000	241	256	246	261	5				0%	15	0%	\$7,000		
29	AC	27	28			20	\$10,000	261	281	261	281	0	r ₉			0%	20	12%	\$11,244		
30	AD	29				15	\$7,000	281	296	281	296	0				0%	15	0%	\$7,000		
31	AE	27	28			14	\$13,000	261	275	262	276	1	r ₉			0%	14	12%	\$14,618		
32	AF	31				20	\$18,000	275	295	276	296	1				0%	20	0%	\$18,000		

(a)

(b)

Fig. 4. Risk Allocator

C. The Risk Simulator (RS)

The Risk Simulator (RS) isn't just a simulation Add-In however it is a Visual Basic for Application (VBA) simulation manipulating code written behind the CPM spreadsheet model. The code manipulates the @Risk simulation Add-In program to repeat, extract, and tabulate results in the proper format for further processes and analyses. The (RS) is responsible for the sequential elimination process of risks to facilitate determining the contribution of each risk on project time and cost [13]. This is done by counting the total number of risks in the RR and allows a loop of

simulations that eliminates one risk after another till reaching the last risk. According to this example, the total number of simulation run is equal to ten is calculated simply by using this rule; (Number of simulation run = Number of risks in the RR + 1)



where the number of risks in the RR is equal to 9 risks and the number of iterations per run is selected to be 10,000. After considering all risks, the simulation calculates the impacted project time and cost versus all confidence levels. All simulation results (Probability density) are then arranged and stored for further analyses by the Contingency Calculator (CC).

D. The Contingency Calculator (CC)

The Contingency Calculator (CC) is responsible for calculating the project-level contingency for both time and cost, at a certain confidence level specified by the user. Moreover, it is responsible for calculating the share of each risk in the calculated contingencies. Fig. 5 shows the typical MCS curves in the (Risk state) for the two cases: (1) considering all risks (R), and (2) considering (R-ri), where one risk ri is eliminated. The contribution of each risk can be determined from the analysis of the simulation results by the end of the elimination process.

Considering the (Risk state) area in Fig.5 the total contingency reserve for time and cost can be calculated using equations (1) and (2) respectively. Whereas, the contribution of each risk can be calculated using equations (3) and (4).

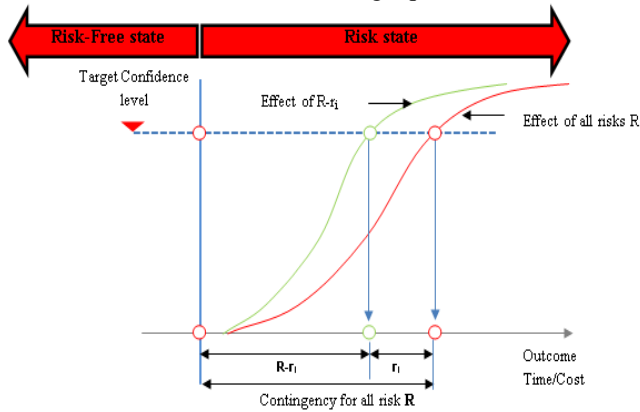


Fig. 5. The elimination process concept

$$TC_R^{(L_t)} = PT_R^{(L_t)} - RFST_P \quad (1)$$

$$CC_R^{(L_c)} = PC_R^{(L_c)} - RFSC_P \quad (2)$$

Where:

- $TC_R^{(L_t)}$ is the time contingency reserve at the time confidence (L_t) for the all-risks (R).
- $PT_R^{(L_t)}$ is the target project time needed to ensure the time confidence (L_t) for time.
- $RFST_P$ is the project-Risk-Free time. "The same definitions are used for the cost according to Equation (2)"

$$TC_{ri}^{(L_t)} = PT_R^{(L_t)} - PT_{R-ri}^{(L_t)} \quad (3)$$

$$CC_{ri}^{(L_c)} = PC_R^{(L_c)} - PC_{R-ri}^{(L_c)} \quad (4)$$

Where:

- $TC_{ri}^{(L_t)}$ is the time contingency reserve shared by the risk (ri) at time confidence (L_t)
- $PT_{R-ri}^{(L_t)}$ is the project time at the time confidence level (L_t) for (R-ri). "The same definitions are used for the cost according to Equation (4)"

The above-mentioned equations were used in this module using spreadsheets functions as shown in Fig. 7. After running

the RS, the user can change the confidence level for time (L_t) and cost (L_c) to realize the total contingency reserve and the impact of each risk on the project. According to this example, the selected confidence is 70% for both time (L_t) and cost (L_c), that corresponds to target time $PT_R^{(70\%)}$ and cost $PC_R^{(70\%)}$ equals 324 days and \$526,789, respectively. Therefore, the contingency reserve for the time $TC_R^{(70\%)}$ is equal to = 324 – 296 = 28 days, where the 296 days is the $RFST_P$ at the project-level according to Eq.1. According to (2) the cost contingency reserve $CC_R^{(70\%)}$ is equal to = \$526,789 – \$485,000 = \$64,789, where the \$485,000 is the $RFSC_P$ at the project-level. Therefore, the additional contingency percentage from the project time and cost Risk-free state are equal to 9.46% and 8.62%, respectively.

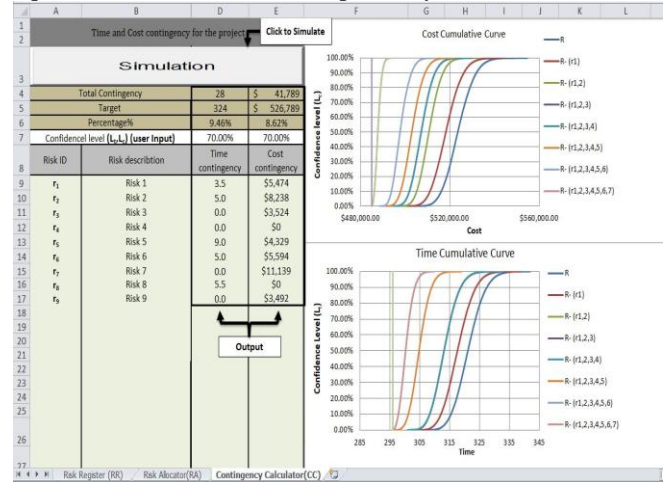


Fig. 6. Contingency Calculator

As for, the required time contingency reserve for risk (r_1) $TC_{r_1}^{(70\%)}$ equals 324 – 320.5 = 4 days, where 320.5 days is the time for (R- r_1) risks $PT_{R-r_1}^{(70\%)}$ corresponding to 70% confidence level (L_t) according to (3). Likewise, the required cost contingency reserve for r_1 risk $CC_{r_1}^{(70\%)}$ is equal = \$526,789 – \$521,315 = \$5,474, where \$521,315 are the cost for (R- r_1) risks $PC_{R-r_1}^{(70\%)}$, according to (4). The same procedures are applied for the remaining risks as shown in Fig. 6.

III. RESULTS AND DISCUSSION

After running the (RS), the total average time taken for the ten simulation run is equal to 20 minutes, with an average of 2 minutes each run. This is done for 23 variables (Risk distributions) allocated to 32 activities by using a CPU processor with an Intel Core i7 CPU 2.20 GHz (8th Gen). The results of the simulation run for the time and cost are demonstrated in Table 1 and Table 2, respectively. The result shows that the increase of confidence level will increase the time and cost contingency selected for the project. Also, it shows that the minimum contingency should be added for the project to avoid the impact of risks are 10 days and \$18,923. On the other hand, the maximum contingency to ensure the avoidance of risk impacts are equal to 48 days, and \$70,930. The analysis for the CC can be summarized, as shown in Fig.7 and Fig.8



Table - I: Project time vs. Confidence level (L_t).

Risks	Time Confidence Level (L_t)										
	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
r_1	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
r_2	1.5	3.5	4	4	4.5	4.5	4.5	5	5	5	7
r_3	0	0	0	0	0	0	0	0	0	0	0
r_4	0	0	0	0	0	0	0	0	0	0	0
r_5	4.5	7	7.5	8	8	8.5	8.5	9	9.5	10	14
r_6	0.5	3.5	3.5	4	4.5	4.5	4.5	5	5	5.5	9.5
r_7	0	0	0	0	0	0	0	0	0	0	0
r_8	0	2	2.5	3	3.5	4.5	5	5.5	6	7.5	14
r_9	0	0	0	0	0	0	0	0	0	0	0
Sum	10.00	19.50	21.00	22.50	24.00	25.50	26.00	28.00	29.00	31.50	48.00

Table - II: Project cost vs. Confidence level (L_c).

Risks	Time Confidence Level (L_c)										
	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
r_1	\$5,896	\$5,023	\$5,217	\$5,294	\$5,291	\$5,338	\$5,385	\$5,474	\$5,579	\$5,595	\$9,901
r_2	\$1,314	\$5,933	\$6,471	\$6,895	\$7,241	\$7,568	\$7,913	\$8,238	\$8,662	\$9,283	\$11,787
r_3	\$3,262	\$3,308	\$3,335	\$3,375	\$3,424	\$3,438	\$3,461	\$3,524	\$3,522	\$3,609	\$4,337
r_4	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0
r_5	\$3,446	\$3,966	\$4,003	\$4,085	\$4,151	\$4,187	\$4,269	\$4,329	\$4,392	\$4,441	\$8,166
r_6	\$1,544	\$4,081	\$4,521	\$4,810	\$5,050	\$5,247	\$5,433	\$5,594	\$5,772	\$6,096	\$8,200
r_7	\$3,446	\$7,607	\$8,324	\$8,883	\$9,394	\$9,940	\$10,490	\$11,139	\$11,945	\$13,054	\$19,916
r_8	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0
r_9	\$15	\$1,174	\$1,657	\$2,037	\$2,377	\$2,720	\$3,082	\$3,492	\$3,998	\$4,734	\$8,622
Sum	\$18,923	\$31,094	\$33,528	\$35,378	\$36,928	\$38,437	\$40,033	\$41,789	\$43,871	\$46,811	\$70,930

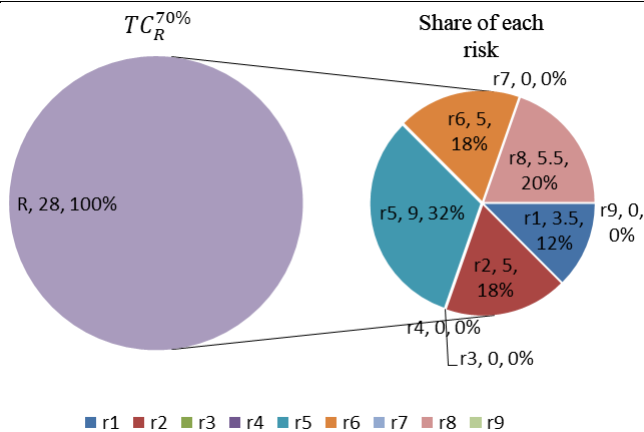


Fig. 7. $TC_R^{(70\%)}$ and the share of each risk at 70 % confidence level

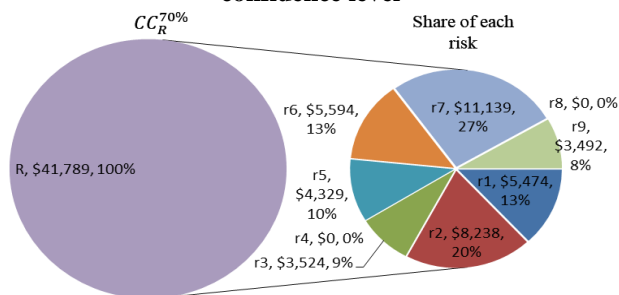


Fig. 8. $CC_R^{(70\%)}$ and the share of each risk at 70 % confidence level

According to the above-mentioned analysis r_3 , r_4 , r_7 , and r_9 have no impact on the time objective, while r_5 , r_8 , r_6 , r_2 and r_1 have an impact with a shared contingency equals to 32%, 20%, 18%, 18%, and 12%, respectively at the selected confidence level 70%. However, r_4 and r_8 have no impact on the cost objective, while r_7 , r_2 , r_6 , r_1 , r_5 , r_3 , and r_9 have a

shared contingency equals to 27%, 20%, 13%, 13%, 10%, 9%, and 8%. It is worth for the decision-maker to treat, transfer, or avoid r_5 and r_7 , as it represents a high contribution from the total contingency for the time and cost, respectively. Hence, it would enhance the user confidence level for the time and cost objective. Otherwise, if the decision-maker accepted those risks, it should be traced and controlled in the construction phase to avoid delays and cost overruns.

IV. CONCLUSION

Risk management is a critical component in project management that determines the project's success. Therefore, determining the contingency reserve and knowing the contribution of each risk is crucial for the decision-maker in responding to the risk. In this paper, the Risk Planning Contingency Model (RPCM) was introduced to estimate the contingency reserve and rank the residual risk for both time and cost using Monte Carlo Simulation at the planning phase. This is done according to a certain confidence level, which is selected by the decision-maker. The RPCM has been applied to a case study case to examine its functions. The RPCM has succeeded in ranking risks dynamically that maintain the selected confidence level. Such ranking would help decision-makers appropriately respond to and/or control the construction risks. The RPCM is a fast and simple tool that can be easily used by the practitioners. As an opportunity for future studies, the proposed model needs to be adapted for the risk response planning. Moreover, the combined ranking of risks would help the decision-maker about the appropriate selection of risk that has the highest impact on both the time and cost.

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AUTHORS PROFILE



Amr Mahmoud Graduate Teacher Assistant, Construction and Building Engineering Department, Arab Academy for Science, Technology & Maritime Transport, Cairo, Egypt. He received his Bachelor degree at 2015 and he is now preparing his M.S in field of risk management. He carries more than 4 years of teaching and administrative experience



Ahmed Elhakeem Associate Professor, Construction and Building Engineering Department, Arab Academy for Science, Technology & Maritime Transport, Cairo, Egypt .He received his MSc and PhD in Construction Engineering and Management with research work involves the use of computational intelligence tools to support efficiently owner/designer/contractors' decisions on high risk and constrained projects. Dr. Elhakeem authored and co-authored more than 50 publications in prestigious journals and international conferences.



Ahmed Elyamany Dr. Ahmed studied Civil Engineering at Zagazig University and was graduated 1999. He obtained the MSc in Construction Engineering 2005 from Zagazig University, Egypt. In 2010, he completed his PhD studies and graduated from North Dakota State University, USA. He is currently working as an associate professor at The British University in Egypt and is a member ASCE and SAVE. He published many articles in Construction Management and Artificial Intelligence.