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RESEARCH PAPER

A Simulation Optimization Approach for The Multi-Objective Multi-Mode Resource Constraint Project Scheduling Problem

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ABSTRACT
According to the real projects' data, activity durations are affected by numerous parameters. In this research, we have developed a multi-resource multi objective multi-mode resource constrained scheduling problem with stochastic durations where the mean and the standard deviation of activity durations are related to the mode in which each activity is performed. The objective functions of model were to minimize the net present value and makespan of the project. A simulation-based optimization approach was used to handle the problem with several stochastic events. This feature helped us to find several solutions quickly while there was no need to take simplification assumptions. To test the efficiency of the proposed algorithm, several test problems were taken from the PSPLIB directory and solved. The results show the efficiency of the proposed algorithm both in quality of the solutions and the speed.

KEYWORDS: *Simulation-based optimization; Resource constraints project scheduling; Multi-objective; Multi-modes.*

1. Introduction

Resource Constrained Project Scheduling Problem (RCPSP) is timing the activities of a project considering their prerequisite relations and the limitations of resources availability. A project has definite as number of activities. Each activity starts once while all of its predecessor complete. Consuming an amount of resources is necessary during the project. Usually, there are two types of renewable and nonrenewable resources in projects and total amount of them are limited [1]. RCPSPs are NP-hard problems [2]. Minimizing the completion time of the project is the most common criterion that has been focused on by researchers. Several models and solutions for a project scheduling problem have been presented, so far. Hartmann [3] studied the RCPSP and proposed competitive Genetic Algorithm (GA) to solve the problem. Multi-mode activities were presented in 1997, for the first time where the activities could start in more than one mode. Properties of the activities like cost, duration and resource requirements are individual in each mode. Project managers optionally can decide about the activities execution modes [4].

With science growth and variety increasing of projects and constraints, multi objective functions has been also considered. Moutinho and Tereso [5] studied a Multi-mode RCPSP (MRCPSP) and presented a mathematical model that objectives were determining start time and modes of activities in order to minimize the total cost of the project. Bagherinejad and Rafie-majd [6] also studied the earliness and delay penalties in the costs of a project. Tavana et al [7] proposed a new multi-objective model to solve a discrete time-cost-quality trade-off problem. Gutjahr [8] proposed a model for a multi-objective MRCPSP under risks that consisted of two objective functions: the makespan and the total cost where costs and periods were supposed to be stochastic in the model. Elazouni et al [9] compared performances of the GA, the Simulated Annealing (SA) and the Frog jumping algorithm to solve the finance consecutive variable scheduling problem. Koulinas et al [10] used a hyper algorithm based on particle swarm optimization for RCPSP. Gomes et al [11]

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proposed five local search meta-heuristic algorithms for multi objective RCPSP and compared the efficiency of the algorithms. Maghsoudlou et al [12] proposed a multi objective invasive weeds optimization algorithm for solving multi skill MRCPSP. The objectives in their research were minimizing the makespan and total cost and maximizing the processes quality. Jun-yan [13] provided a literature review of schedule uncertainty control in projects. Hao et al [14] offered a MRCPSP with stochastic periods and a multi objectives distribution estimate algorithm. Ghamginzadeh et al [15] solved a multi objective model of a MRCPSP using a cuckoo optimization algorithm. We developed that model and solved it with a simulation based algorithm in the current paper.

The simulation is one of the most applicable techniques of Operation Research (OR) which shows the virtual process operation of the actual model in time. Studying the simulated model and its results drives to find the features of a real system. The simulation monitors the trend of the real systems in time of its evolution. The set of functional assumptions including constrains and objectives expresses in format of symbolic mathematical equations and the feasible changes may be applied on the system very quickly and easily. The basic steps of revising the simulated model are configuring the problem, objectives determination, modeling, data gathering, programing, validation, run and analysis of the results [16].

SIMSUM1 [17] is an innovative combined algorithm including discrete event simulation and a relaxation technique of decision variable to solve specific problems with binary variables. In fact, the name of SIMSUM1 is retrieved from two words: the simulation and the summation. Azimi [17] proved the efficiency of applying the SIMSUM1 in binary models and solved the three known combinatorial problems: the Dynamic Facility Layout Problem (DFLP), the Graph Labeling Problem (GLP) and the Travelling Salesman Problem (TSP). These problems have two similar features: 1) they are 0-1 programing models 2) summation of all decision variables is restricted to be one. The makespan in the real projects would be changed in different conditions. One of the factors which cause the difficulties in the estimation of an activity duration is the risks of the project. In this research, we discussed a developed version of multi-objective MRCPSP. The paper is structured as follows:

In section 2, the model characteristics are described and the mathematical model is presented. In section 3 the major steps of our proposed approach and the experiment results are provided and finally, the conclusions and suggestions for future researches are provided in Section 4.

2. Model Description

A multi objective MRCPSP with a set of activities and prerequisite relations was investigated in this research. The relations have defined as a graph of G=(V, E). In this graph, V and E are the sets of the activities and the arcs, respectively. The precedence relations are depicted in the format of Activity On Node (AON) network. In this type of network, we have to assume two dummy activities at the beginning and the end of a project. Then, durations and required resources for the start and the finish activities would be null. Fig. 1 depicts such a network.

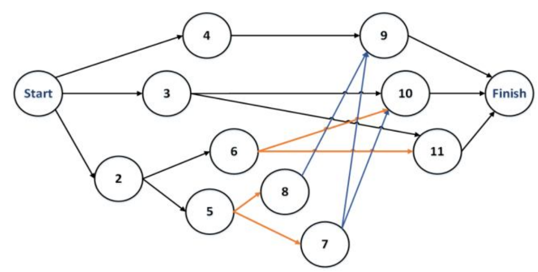

Fig. 1. AON network of project.

To accomplish a project, some renewable and nonrenewable resources are needed to be consumed. Each activity can perform in more than one mode, duration times are stochastic, stochastic parameters (Mean and Standard Deviation) and the execution costs of duration of activities are defined and set for each mode. For starting each activity, all of its predecessors should be finished.

2.1. Parameters and indexes

Before developing the model, defining the parameters and the associated nomenclatures are necessary, which are as follows,

Sets:

I	Set of modes, i = 1, …, I
J	Set of activities, j = 1, …, J
K	Set of one type resources, k = 1, …, K
T	Set of time periods, t = 1, …, T
I_j	Set of modes for activity i
θ	Set of precedence relations

Parameters:

d_{ij}	Duration of activity j at mode i
μ_{ij}	Mean for duration of activity j at mode i
δ_{ij}	Deviation standard for duration of activity j at mode i
R_k	Total available of renewable resource k
r_{ijk}	Required renewable resource k
N_k	Total available of nonrenewable resource k
η_{ijk}	Required nonrenewable resource k
α	The inflation rate
c_{ij}	Cost of activity j at mode i
Decision variables:	
x_{ijt}	A 0-1 variable which takes 1 if activity i is executed in mode j in period t

2.2. Problem model

As mentioned before a multi-objective problem was considered in this study. The objective functions were to minimize the makespan and the Present Value of Costs (PVC). Based on to the parameter definitions, the mathematical model could be written as follows:

Problem 1:

$$Z_1 = Min \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T} C_{ij}X_{ij}(1+\alpha)^{-t} \qquad (1)$$

$$Z_2 = Min \sum_{i=1}^{I} t.X_{ijt} \qquad (2)$$

$$\sum_{i=1}^{I}\sum_{t=1}^{T} x_{ijt} = 1 \qquad (3)$$

$$\sum_{i=1}^{I}\sum_{t=1}^{T} t.x_{ijt} \leq \sum_{i=1}^{I}\sum_{t=1}^{T}(t-d_{i,j'})x_{ij't} \qquad (4)$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J} r_{ijk} \sum_{t-d_{ij}}^{t} x_{ijt} \leq R_k \qquad (5)$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J} \eta_{ijk} \sum_{t=1}^{T} x_{ijt} \leq N_k \qquad (6)$$

$$d_{i,j'} \sim N(\mu_{ij'}.\delta_{i.j'}^2) \qquad (7)$$

$$x_{ijt} \in \{0, 1\} \qquad (8)$$

In Problem 1, the objective functions of the problem are written as (Eq.1) and (Eq.2). The objective function (1) is to minimize the PVC of the project. Minimizing the last activity completion time in a project is equivalent to minimizing the project completion time. Function (2) is to satisfy the time horizon of the project. Eq.3 ensures that each activity starts exactly from one time and just in one mode. Eq.4 describes the precedence relations between activities and means that each activity can start when all of its predecessors have completed. θ is the set of Related activities. If activity j be a predecessor of activity j' then (j, j') $\in \theta$. Eq.5 and eq.6 are constraints that ensure availability limitation of renewable and nonrenewable resources during the project respectively. Eq.7 expresses that execution duration of each activity is stochastic function of normal distribution with given statistic parameters. x_{ijt} is decision variable of the model. If activity j starts in mode i at time t then x_{ijt} is equal to one otherwise is equal zero (Eq.8).

3. Solution Approach

The SIMSUM1 [17] is a combined algorithm consisting of discrete events simulation and a relaxation technique for decision variable to solve 0-1 programming models which have a special constraint that restrict the summation of all decision variables to be one. Constraints (3) and (8) in Problem 1 makes the model suitable to use SIMSUM1 method. At the beginning, this algorithm relaxes the decision variable in constraint set (8). The resulting relaxed model is a linear continuous one; so it could be solved using any normal and simple algorithm like Simplex. The optimum solutions of the relaxed problem have two main characteristics. First, the summation of variables related to each activity mode is equal to 1 (Constraint set (3)). Secondly, each decision variable is between 0 and 1. So, the optimum solutions could be assumed as a distribution function for each activity. Finally, it assumes the result value of the decision variable in primitive solution as probability of occurrences in the simulated model. Finally, these optimal values are used in a simulation model for Problem 1 where all Constraints are coded in the simulation software and these optimal values are used as probability functions. For example, if in the optimal solutions we have $x_{111} = 0.7$ and $x_{121} = 0.3$, it means that activity 1 is executed in mode 1 with the probability of 0.7 while for mode 2, the probability is 0.3. Therefore, at each replication of the simulation model, a random feasible solution is generated for Problem 1, very quickly. Since the probabilities are taken from the optimum solutions, the simulation model is smart enough to focus on potential good solutions and avoid blind searches.

3.1. Weighted objectives function

Usual mathematical linear methods are not able to solve multi-objective models. Thus, before starting to solve the problem with the proposed algorithm, it is necessary to transform the multi-objective model to a single objective type. To do so, summation of weighted objectives is regarded as a single objective function. The objectives' weights are assumed equal based on the expert judgments in the National Iranian Oil Company (NIOC). Then Eq.9 can be written as the single objective of the model as follows:

$$MIN\ Z = MIN\ (W_1 Z_1 + W_2 Z_2) \tag{9}$$

Problem objectives are PVC and project time horizon. Genre of cost is money and genre of makespan is time; therefore they are ineligible for summation. To make them scalable, each objective function divided by the maximum value of that function. Then it multiplied by its related weight. Eq.10 is used to calculate the Z.

$$Z = W_1 \frac{Z_1}{Max\ Z_1} + W_2 \frac{Z_2}{Max\ Z_2} \tag{10}$$

3.2. Relaxation

In this step, decision variables which are 0-1 are relaxed to have continuous values between 0 and 1. The eq.11 is replaced by the eq.8, as follows:

$$0 \leq x_{ijt} \leq 1 \tag{11}$$

Now we have a continuous linear programing model. The relaxed model could be solved using GAMS software. Note that the activity durations are assumed to be deterministic and equal to given mean duration per activity. Tab. 1 shows the optimal solution for a problem with 10 activities. In this sample example, each task could be run in two main modes.

Tab. 1. Output of GAMS solver

Activity (j)	Mode 1	Mode 2
1	1	0
2	0	1
3	0	1
4	0	1
5	0	1
6	0	1
7	0	1
8	0.667	0.333
9	1	0
10	0.208	0.792
11	1	0
12	1	0

3.3. Simulation

In the next step, the model was simulated using ED 7.2 software. All constraints in Problem 1 was coded in the simulation software using its coding language "4DScript". Fig. 2 demonstrates the simulated AON network of a project in the software.

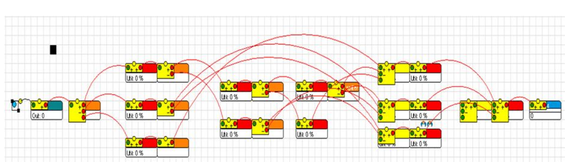

Fig. 2. AON network of a project in the simulation software

At the beginning of each replication, a number of commands are executed. These commands defines the duration time of each task based on the probabilities which are coming from optimal solution of Problem 2. For example, the execution mode for activity 8 is defined by a Bernoulli probability function (see Table 1). It means that at each replication, activity 8 is executed in mode 1 with a probability of 0.67 or in mode 2 with probability 0.33. For decision variables which have the optimal value of 1 or 0, a 5 percent range was considered. For example, if in the optimal solution of Problem 2, the value for activity 3 in mode 1 is 1, we set it as 0.95 in the simulation software to have a 5% chance to have the value of 0. The simulated model also meets the renewable constraints, so that each renewable resource is considered as an operator who was called when it is needed for an activity and is released after that activity is finished. This trick helps us to model the renewable constraint in the simulation software. The number of operators is limited and when an operator is working in a workstation, that unit of resource cannot be used for other workstations (activities). At the beginning, at the end, and during the execution of each activity, all data such as duration (because the execution time of each activity in each mode is stochastic), cost and execution mode are recorded in a table. The project is replicated several hundred times and all information is recorded.

Tab. 2. Execution modes (i) and activity durations (j) for 20 replications

	2		3		4		5		6		7		8		9		10		11		Finish
run	mod	dur	mod	dur	mod	dur	mod	dur	mod	dur	mod	dur	mod	dur	mod	dur	mod	dur	mod	dur	makespan
1	2	9.2	2	10.4	2	15.5	2	7.8	2	4.6	2	6.9	2	12.8	1	1.8	2	0.8	1	6.6	31.61
2	1	3.2	2	4.4	2	8.1	2	7.5	2	3.9	2	11.2	1	3.0	1	2.0	2	0.9	1	7.8	23.87
3	2	10.0	2	11.3	2	15.8	2	7.3	2	5.4	2	11.9	1	3.5	1	1.9	2	1.1	1	6.5	31.14
4	2	7.2	2	8.1	2	12.3	2	6.8	2	2.5	2	7.1	2	7.3	1	1.5	2	0.7	1	6.2	22.72
5	2	10.5	2	11.7	2	16.7	2	6.0	2	3.4	2	8.4	1	4.4	1	1.8	2	1.0	1	5.0	26.75
6	2	8.7	2	9.9	2	15.1	2	7.1	2	5.0	1	2.6	2	8.7	1	2.0	2	1.3	1	6.2	26.52
7	2	11.1	2	12.5	2	17.4	2	7.3	2	4.9	2	8.8	1	2.2	1	1.6	2	1.0	1	5.7	28.80
8	1	3.0	2	3.8	2	8.9	2	6.6	2	3.8	2	9.6	1	6.0	1	2.1	2	1.5	1	6.2	21.30
9	2	7.8	2	8.7	2	12.8	2	5.3	2	4.4	2	11.8	1	4.2	1	1.9	2	1.5	1	6.2	26.70
10	2	8.1	2	9.6	2	15.1	2	6.6	2	2.9	1	3.9	1	9.4	1	2.4	2	0.9	1	5.6	26.58
11	2	9.0	2	10.0	2	15.4	2	6.0	2	4.8	2	12.2	1	4.2	1	1.6	2	0.7	1	6.6	28.78
12	2	8.9	2	9.7	2	14.0	2	7.7	2	3.6	2	5.0	1	4.4	1	1.7	2	1.2	1	3.5	23.26
13	2	10.6	2	11.6	2	15.8	2	8.5	2	3.9	2	6.2	1	3.7	1	1.9	2	1.0	1	5.8	27.26
14	2	7.1	1	1.1	2	14.1	2	6.4	1	8.4	2	7.6	1	4.4	1	2.3	2	1.0	1	13.5	29.01
15	2	7.9	2	8.5	2	13.2	2	7.2	2	2.8	2	9.7	1	3.9	1	1.7	2	1.1	1	7.8	26.37
16	2	8.7	2	9.8	2	16.7	2	6.7	2	3.6	2	8.6	2	8.7	1	1.8	1	1.0	1	3.5	25.86
17	2	9.3	2	10.0	2	14.9	2	6.6	2	4.7	2	12.2	1	3.4	1	2.2	2	1.1	1	6.8	30.32
18	2	10.0	2	10.9	2	15.8	2	8.4	2	3.5	2	6.0	1	3.7	1	2.0	2	1.1	1	6.4	26.45
19	2	8.7	2	10.1	2	14.3	2	8.4	1	7.3	2	13.4	2	9.1	1	2.3	1	0.9	1	7.7	32.81
20	2	9.8	2	10.9	2	15.8	2	5.9	2	2.6	2	10.5	2	6.2	1	1.9	2	1.1	1	5.9	28.07

Tab. 3.objective values & costs of 20 replications

run	2	3	4	5	6	7	8	9	10	11	Makespan	Total cost	Z
1	15	12	17	17	10	15	7.3	8.5	8	14	31.6117871	114.1207	1.5829
2	16	12	17	17	10	15	8	8.5	8	14	20.5661676	116.4021	1.6
3	15	12	17	17	10	15	8	8.5	8	14	19.8239103	118.4543	1.5862
4	15	12	17	17	10	15	7.3	8.5	8	14	22.7192371	115.9264	1.5689
5	15	12	17	17	10	15	8	8.5	8	14	20.8474584	118.3086	1.5776
6	15	12	17	17	10	16	7.3	8.5	8	14	21.2966816	118.264	1.5854
7	15	12	17	17	10	15	8	8.5	8	14	24.104705	115.4687	1.579

8	16	12	17	17	10	15	8	8.5	8	14	23.26425	116.5031	1.5927
9	15	12	17	17	10	15	8	8.5	8	14	24.6928095	115.5515	1.5857
10	15	12	17	17	10	16	8	8.5	8	14	22.4555466	117.8492	1.5973
11	15	12	17	17	10	15	8	8.5	8	14	24.1235314	116.1984	1.5833
12	15	12	17	17	10	15	8	8.5	8	14	25.2405534	115.1469	1.5785
13	15	12	17	17	10	15	8	8.5	8	14	22.8175573	117.6941	1.579
14	15	12	17	17	11	15	8	8.5	8	14	25.4847826	115.129	1.6028
15	15	12	17	17	10	15	8	8.5	8	14	24.199447	116.4931	1.584
16	15	12	17	17	10	15	7.3	8.5	8.3	14	24.3804916	116.3528	1.5706
17	15	12	17	17	10	15	8	8.5	8	14	25.7198564	115.0557	1.5885
18	15	12	17	17	10	15	8	8.5	8	14	23.7376103	117.1084	1.5773
19	15	12	17	17	11	15	7.3	8.5	8.3	14	25.9493682	114.9055	1.5857
20	15	12	17	17	10	15	7.3	8.5	8	14	25.8613509	115.0282	1.5727

Table 2 shows the selected modes and the durations for the first 20 replications of the project with 11 activities. In that project, each activity has just two modes.

Tab. 3 shows the costs of activities for the same replications of the project. Each project is replicated until 1000 randomly feasible solutions are found.

3.4. Solutions updating

Costs in the achieved simulation solutions are not in the form of PVC, and also the constraint of nonrenewable resources is missed. So the answers needed to be fixed in this step.

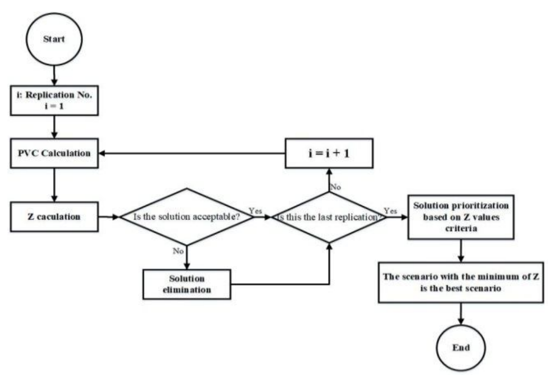

Fig. 3. Updating flowchart

Fig. 3 illustrates the flowchart for fixing the simulation solutions. We used Microsoft excel Visual Basic Application (VBA) 2016.

Tab. 4. first 10 update solutions

Iteration No.	MAKESPAN	PVC	Z
616	22.78417	114.84720	1.55546558
1324	19.89848	116.09567	1.559352358
860	26.64547	113.92344	1.559763337
952	22.95479	115.19702	1.560624119
1281	25.40853	114.39962	1.560679337
1108	22.69547	115.28989	1.560727633
702	24.10298	114.88130	1.561380189
436	21.47068	115.81285	1.562289144
184	21.83038	115.70776	1.562447392
964	26.53182	114.18013	1.562555954

Tab. 4 shows the best first 10 fixed solutions for a sample problem which was replicated 1489 times in the simulation software. The fixed operation detected 276 infeasible solutions and eliminated them. Then it sorted them based on the objective functions values. The 616th replication was selected as the best case scenario with the minimum for our objective function. Tab. 5 shows the values of the decision variables in this replication.

Tab. 5. values of decision values

Activity (j)	Mod (i)	Duration (t)
Start	1	0
2	1	2.464555
3	2	3.614131
4	2	9.545875
5	2	5.842477
6	2	5.17388
7	2	6.306049
8	2	8.103368
9	1	1.927907
10	2	1.104258
11	2	10.73501
Finish	1	0

In the results of the aforementioned example, the best solution for the PVC function was found in the 112th replication, which was equal to $ 111.9. In that replication, the time function value was 40 days. Also the best solution for the second function was found in 629th replication at $ 119 and 18 days. These results show that the best approach for each objective would independently drive the other objective to its worst case. Finally results are depicted in Figure 4 as the Pareto front for the problem.

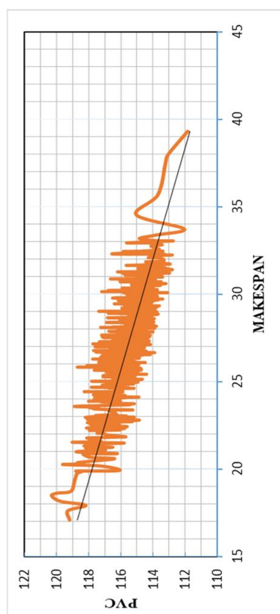

Fig. 4. Efficient scenarios curve

Note that changing the objective weights in the fixing step without considering the basic weights of the algorithm affects the diagram slope. Hence, the temporary objective weights can be assumed by the solver at the start; then the weights can be changed according to the project manager's preferences in the fixing step. The proposed approach was tested over 25 random instances including 10 small, 10 medium and 5 large size problems. Tab. **6** shows the related experiment results.

Tab. 6. Experiment results

Scale	PROBLEM	Activities (j)	MAKESPAN	PVC	Z*	Time (sec)
Small	P1	10	23.1	112.6	1.55	20.47
	P2	10	19.9	116.1	0.86	25.09
	P3	10	18.9	117.4	0.83	22.12
	P4	10	17.8	118.5	0.81	19.49
	P5	10	21.3	115.7	0.85	17.67
	P6	10	19.7	119.6	0.85	19.37
	P7	10	18.3	122.3	0.84	20.09
	P8	10	21.7	119.7	0.89	18.66
	P9	10	20.6	125.4	0.91	19.75
	P10	10	22.4	124.5	0.89	19.84
Medium	P11	15	27.9	311.9	0.89	25.95
	P12	15	29.8	315.5	0.83	31.39
	P13	15	40.8	320.8	0.82	29.2
	P14	15	50.9	311.9	0.84	29.01
	P15	15	44.8	319.3	0.9	26.87
	P16	15	40.3	324.5	0.91	23.26
	P17	15	46.7	330.6	0.93	28.33
	P18	15	55.4	335.6	0.84	28.42
	P19	15	58.4	340.9	0.9	26.46
	P20	15	59.2	353.8	0.86	28.35
Large	P21	30	96.3	400.9	0.88	69.37
	P22	30	97.9	495.3	0.94	60.29
	P23	30	91.7	501.6	0.92	71.26
	P24	30	101.2	511.8	0.9	65.03
	P25	30	110.8	586.4	0.92	85.03

4. Conclusion

In this research, a Multi-Objective MRCPSP model with non-deterministic duration times for project activities was developed. Activity durations were defined as the probability distribution functions to minimize the PVC and the makespan objectives. We solved the model using a simulation-based optimization method called SIMSUM1. The major steps of the algorithm were: 1) Decision variable relaxation and transmutation of the multi-objective problem to a linear single objective model 2) Solving the new linear model 3) Simulating the model by the results of the linear model and 4) Solution fixing. The simulation-based approach helped us to set and model the stochastic parameters like durations. As a result, we could connect the mathematical programming results to the simulation technique to construct an approach for optimizing the problem. This approach and its promising results could be applied in other combinatorial problems such supply chain networks (SCN) and reliability theory. In this study, just costs were included in the first objective function while in real projects, the budgets or revenues are positive cash flows to be included in the objective function. So changing the first objective function to a Net Present Value (NPV) is suggested for future researches. Also, it was assumed that the capacity of all resources is deterministic while in real applications, the availability of each resource could be probabilistic.

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