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Optimal construction scheduling: A trade-off approach between project time, cost, and residual flexibility

Original Article

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Abstract

Achieving project scope on time at minimum cost is important for contractors to ensure profitability. Existing models attempt to arrive at optimal schedules, but without considering the delays that occur during construction, which have been statistically proven to occur on most projects. Since these schedules cannot guarantee delays recovery, it cannot be claimed optimal. Hence, this paper attempts to incorporate delay recovery during construction into the optimal schedule generation. Recovering delays that occur over the life of the project construction requires a set of project crashes for the remaining and incomplete activities in the project. Ensuring that the incomplete activities can be crashed at low cost in conjunction with the progress of the project construction represents a proposed solution to such a problem. And it is called in this paper the schedule's residual flexibility. In developing an optimal schedule, a trade-off between the project time, cost, and residual flexibility is considered.

1. INTRODUCTION

Time Cost Trade-off (TCT) is a planning technique developed to create optimal schedules targeting minimal project cost and/or time. With the fact that construction projects encounter unforeseen events that lead to delays from planned, a set of consecutive corrective actions are required during the construction phase to recover those delays, meet deadline, and avoid penalties. In this case, crashing the project will be the key to meeting deadlines and avoiding penalties. Project crashing is a methodology for shortening project duration by reducing the time of one or more of its critical activities. The crashing is achieved by allocating more resources to these activities to be shortened or by changing the method used for faster construction methods, which correspondingly increases their direct costs.

Researchers have followed different approaches to solve the TCT problem but most of them focus on creating the optimum schedule considering that all activities will start and finish in their scheduled times, regardless of the delays that occur during construction. The resulted schedule (the schedule claimed to be optimal) from these methods may not be flexible enough to recover those delays. For example, creating a schedule where the activities at the end of the project have been crashed to their minimum durations. Thus, the resulted schedules from these methods cannot guarantee that the project will finish within deadline and/ or with minimum cost.

Apparently, there is still a need for scheduling method that considers the cost of delay recovery on the time-cost trade-off optimization. The main objective of this study to fill this important knowledge gap. This paper introduces a systematic method to create flexible project schedules by employing the concept of schedule residual flexibility to schedule optimization in planning stage and choosing the corrective action plan that maintains flexibility throughout construction stage.

1.1 Previous research

Researchers took different approaches to solve the time cost trade off problem (TCTP). These approaches can be classified into three main groups: Heuristic approaches, Mathematical models, Evolutionary algorithms.

Examples of heuristic approaches include Siemens's effective cost slope model[1], and Moselhi's structural stiffness method[2]. These heuristic approaches are easy to understand but they don't guarantee optimal solutions.

Mathematical models utilize linear programming, integer programming, or dynamic programming. In 1961, linear relationship was considered[3] between duration and cost within activity and used linear programming as the tool to solve the TCTP. Integer programming was used[4] to solve time-cost problems including both linear and discrete relationships within the same activity. Used a combination of linear programming and integer programming[5] to solve the TCTP which is easier to formulate than previous mathematical models.

Evolutionary algorithms (EAs) are stochastic search methods that mimic the natural biological evolution and/or the social behavior of species[6]. Genetic algorithm procedure was developed[7] to provide a practical optimization model for time–cost trade-off analysis. A multi-objective approach was presented[8] that optimizes total time and total cost of a construction project simultaneously by utilizing genetic algorithms. A comparative study of five different evolutionary algorithms was done[6] to optimize a construction time cost trade off problem. A discrete particle swarm optimization model was developed[9] to optimize large scale construction TCTP in short time.

More recent studies tend to focus more on considering practical and real-life factors on schedule optimization to produce more reliable schedules as these factors in many times have high impact on project scheduling. Menesi *et al*[10] presented a model for solving time-cost tradeoff in large scale projects that are challenged by many constraints including strict deadlines and resource limits. In this paper constraint programming (CP) is used as mathematical optimization technique to resolve both resource constraint scheduling (RCS) and time-cost tradeoff (TCT) simultaneously. Risk and quality were considered in mathematical model for project crashing[11]. The objective of this study is to minimize the total project cost while crashing project considering practical factors the quality and risk. Milat *et al*[12] solved Resource-Constrained Project Scheduling Problem (RCPSP) with two objectives. The first objectize function is minimizing the project duration, the second objective function is to improve the resilience of baseline schedule. In their study they improved the resilience of baseline schedule by maximizing the free floats for the early activities in the schedule.

1.2 Schedule flexibility

Hegazy and Abuwarda in 2019[13] introduced the term residual flexibility and defined schedule flexibility as the ability of the schedule to accommodate further corrective actions. They presented a study to measure the residual flexibility of any proposed corrective action plan, and they concluded that recovering delays on short-term costs more but allow for more flexibility for the rest of the project, while recovering delays on full horizon may cost less but allows for less flexibility for the rest of the project. Still if the original project plan doesn't have flexibility for the activities at the end of the project, the project will most likely get delayed no matter what the corrective action plan is.

Turkoglu *et al*[14] have considered flexibility through assigning crash duration consumption rate to each activity, where the maximum crash duration of each activity is multiplied by a factor ranging from (0% to 100%) this factor is set according to the planner's estimation for each activity. Despite that this research aims to achieve flexibility in project scheduling but crash duration consumption rate must be assigned to each activity independently according to the planner's estimation and didn't provide a systematic way to achieve a flexible project schedule.

From the literature conducted on construction planning and scheduling, many models have been developed to solve the TCTP considering various factors including resource constraints, risk, quality, overlapping activities in fast-track projects, and uncertainties that is mostly resolved by incorporating the free floats of activities into the objective function of the optimization problem. But only a few researchers have discussed schedule flexibility and considered it as a function of the activities unused modes of construction. Also, the few research done on this matter did not provide a systematic approach to achieving flexibility in construction schedules.

2. RESEARCH PHILOSOPHY AND CONCEPTS

The main philosophy considered in this research:

1. Incorporating a flexibility measure during time cost tradeoff optimization.
2. Having corrective action plan that maintains flexibility.

Some concepts are introduced to incorporate flexibility as follows.

Each activity has different construction modes, each differs in cost and duration. The duration difference between the mode with the minimum duration and the mode with the maximum duration is represented by the term "Total crashing buffer" as shown in Equation (1)

$$TB_i = d_{max.\ i} - d_{min.\ i} \quad (1)$$

where,

TB_i is the total crashing buffer of activity i.

$d_{max.\ i}$ is the maximum duration of activity i.

$d_{min.\ i}$ is the minimum duration of activity i.

Performing time cost tradeoff optimization selects the construction mode for each activity that results in optimized total project cost and/or duration. The duration difference between the selected mode and the mode with the minimum duration is represented by the term "Remaining crashing buffer" as shown in Equation (2). This term was introduced to measure the capability of each activity to be compressed at any given time during construction. (2)

$$RB_i = d_{m\,i} - d_{min.\ i}$$

where,

RB_i is the remaining crashing buffer of activity i.

dm_i is the duration of the selected mode of activity i.

Fig. 1 illustrates the two terms "Total crashing buffer" and "Remaining crashing buffer".

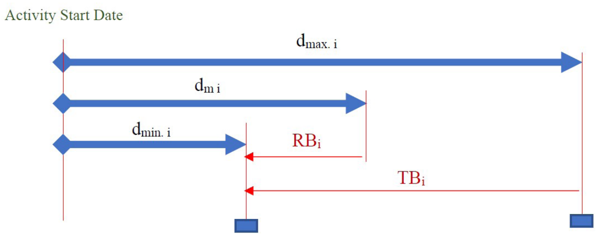

Fig. 1: Total crashing buffer and remaining crashing buffer of an activity.

It can be concluded that the crashing buffer percentage for each activity can be considered as.

$$Crashing\ buffer\ \%\ i = \frac{RB_i}{TB_i}\ \% \qquad (3)$$

The residual flexibility in this study is considered to be function of the activities unused modes of construction and is represented by the term "Crashing buffer %". Incorporating flexibility to time cost tradeoff optimization can be done by controlling the compression of activities during optimization such that the activities that start earlier in the schedule will be allowed to be compressed with higher percentage compared to the activities that start later to allow for flexibility as the project goes on. Thus, the crashing buffer percentage should be more for the late activities. So, compression of activities during time cost tradeoff optimization will be constrained by the start times of activities relative to the total project duration through using the factor "Minimum allowed durations", where each activity is not allowed to have durations less than the "Minimum allowed durations" during schedule optimization. Calculating the factor "Minimum allowed durations" is through Equation (4).

$$d_{all.\ i} = d_{max.\ i} - (TB * Max.\ cr\ \%_{\ i}) \qquad (4)$$

where,

$d_{all.\ i}$ is the minimum allowed duration of activity.
Max. cr % $_i$ is the maximum crash percentage of activity.
ES $_i$ is the early start time of activity.
TD is the total project duration.

The value of "Max. cr %" determines the minimum amount of residual flexibility for each activity where activities with lower values of "Max. cr %" means more residual flexibility is considered for those activities. So, in order to optimize the schedule considering that the activities that start late should have more residual flexibility, the "Max cr. %" is proposed to be function of the start times of the activities as shown in equation (5):

$$Max.\ cr\ \%_{\ i} = 1 - \left(\frac{ES_i}{TD}\right)^n \qquad (5)$$

where,

ES $_i$ is the early start time of activity i.
TD is the total project duration.

The early start time of activities is chosen over the late start times to allow the non-critical activities to be compressed with higher percentages to provide more crashing options. Raising the degree of the term (ES/TD) to "n" degree determines the amount of the required residual flexibility in schedule, where considering a linear function (i.e., n = 1) allows for more residual flexibility for all activities but severely limit the crashing options. While considering a square function (i.e., n = 2) the amount of residual flexibility decreases but allows for more crashing options. And generally, by increasing the degree 'n" the residual flexibility decreases and more crashing options become available. Figure 2 illustrates the relation between "Time" and "Max. cr. %" of activities considering different degrees.

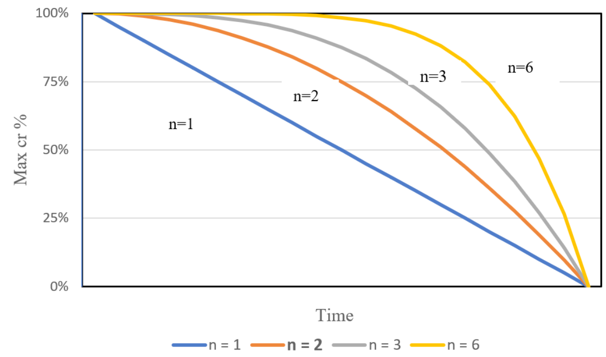

Fig. 2: Early start time and Max cr % of activities

The choice of the degree "n" can vary according to each project's requirements. In this study a square function is considered (i.e., n = 2). So, the "Max cr %" considered in this study is as shown in Equation (6).

$$Max.\ cr\ \%_{\ i} = 1 - \left(\frac{ES_i}{TD}\right)^2 \qquad (6)$$

After incorporating flexibility in time cost tradeoff optimization there must be a well-defined corrective action plan to preserve flexibility over the construction phase of the project. Hegazy and Abuwarda (2019) studied different corrective action plans and discussed the recovery of delay on different horizons which are: short-term, longer compression horizon on short-term, long-term, and full horizon as shown in Fig. 3. They concluded that recovering delays in short term costs more but allows for flexibility for the rest of the project but recovering delay on long-term or full horizon may cost less but consumes the ability of the schedule to absorb future delays. However, most projects have strict deadlines and penalties to be paid in case the deadline was violated. Hence by considering the penalties in the total cost of these projects, utilizing a short-term recovery plan is expected to cost less as it preserves flexibility and could keep the project within deadline and so prevents penalties. Hence, a type of short-term recovery plan is chosen as a corrective action plan.

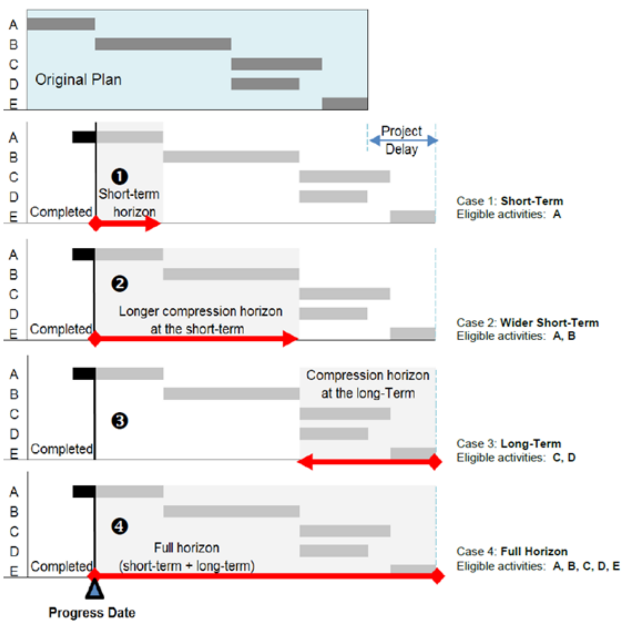

Fig. 3: Recovery plans (Source: Hegazy and Abuwarda 2019)

The strategy followed to recover delays that occur during construction is:

1- The project is divided into periods as shown in Figure 4.

2- Delays occur at any time during the construction of projects, corrective actions shall take place after the end of each period to recover those delays.

3- Implement short term corrective actions to recover delays by specifying a horizon in which only the remaining activities that are scheduled to finish in this horizon will be crashed to recover delays.

4- In this study the recovery horizon is considered to be the period that is about to start at the time of taking corrective actions. For example, the delay that occurs during "Period 1" shall be recovered through crashing the remaining activities that is scheduled to finish in "Period 2". Figure 4 illustrates the recovery horizons considered in this study.

At the time of taking corrective actions, a decision should be made regarding the activities that are in progress whether to allow crashing of those activities or not. This decision should be dependent on many factors including the duration of the activity and the percentage completed of that activity at this time, also the availability of resources to be quickly assigned to these activities. And in some cases, if crashing these activities requires change in the construction method it may not be possible to crash these activities after it has started. However, for the purpose of this study the rule followed for crashing the in-progress activities is that if more than 50% of the original duration of that activity is remaining at the time of taking corrective actions the activity is allowed to be crashed as shown in the illustrative project schedule in Fig. 4.

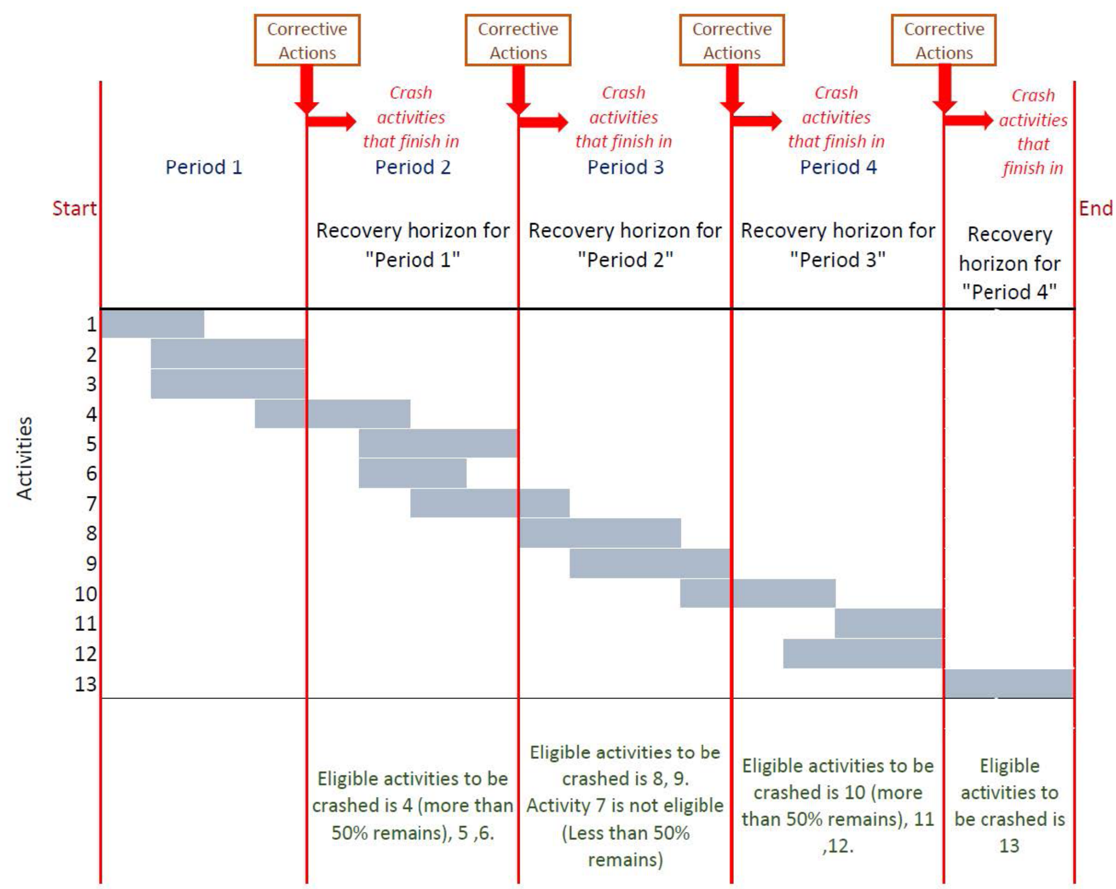

Fig. 4: Recovery horizons

3. RESEARCH METHODOLOGY

The proposed scheduling method aims to incorporate schedule flexibility in time cost tradeoff optimization, the following methodology have been followed in this study:

1. Develop an advanced spreadsheet CPM model for project schedule that considers different relationship types among activities and can facilitate crashing.
2. Calculate the flexibility measures considered in this study "Total crashing buffer, Remaining crashing buffer, Maximum crash percentage, Minimum allowed durations" for each activity.
3. Divide the project timespan into periods, and after the end of each period corrective actions shall take place to recover the delays that occurred
4. Choose a short-term recovery plan for corrective actions.
5. Optimize schedule using genetic algorithms (GAs). GA is the most commonly used evolutionary algorithm for optimizing construction schedules. The reason for this is that GA has been shown to be effective in solving a variety of construction scheduling problems, including problems with resource constraints, multiple objectives, and uncertainty.
6. Case study of 63 activities was used to test the performance of the proposed scheduling method against existing methods. Three scheduling methods shown in Table 1 were applied for the same case study and delay scenarios were assumed at different stages of the project to test the ability of each to recover delays and with how much cost.

Table 1: Comparison between existing methods and proposed method

	Existing methods		Proposed method
	1st method	2nd Method	3rd method
Optimization parameters	Time, cost	Time, cost	Time, cost, flexibility
Corrective action plan	No definite corrective action plan "Full horizon"	Short term recovery	Short term recovery

4. MODEL EXPERIMENTING

The case study used to experiment the model is adapted from[15]. The problem consists of 63 activities each has up to five modes of construction. The indirect cost and penalties per day are set to \$3500 and \$9000 respectively with 626 days as a deadline. Table 2 shows the data for the case study.

Table 2: Case study data (Source: Sonmez and Bettemir 2012)

Act. No.	Pred.	Mode 1		Mode 2		Mode 3		Mode 4		Mode 5	
		Dur.	Cost	Dur.	Cost	Dur.	Cost	Dur.	Cost	Dur.	Cost
		(days)	$	(days)	$	(days)	$	(days)	$	(days)	$
1	-	14	3750	12	4250	10	5400	9	6250	-	-
2	-	21	11,250	18	14,800	17	16,200	15	19,650	-	-
3	-	24	22,450	22	24,900	19	27,950	17	31,650	-	-
4	-	19	17,800	17	19,400	15	21,600	-	-	-	-
5	-	28	31,180	26	34,200	23	38,250	21	41,400	-	-
6	1	44	54,260	42	58,450	38	63,225	35	68,150	-	-
7	1	39	47,600	36	50,750	33	54,800	30	59,750	-	-
8	2	52	62,140	47	69,700	44	72,600	39	81,750	-	-
9	3	63	72,750	59	79,450	55	86,250	51	91,500	49	99,500
10	4	57	66,500	53	70,250	50	75,800	46	80,750	41	86,450
11	5	63	83,100	59	89,450	55	97,800	50	104,250	45	112,400
12	6	68	75,500	62	82,000	58	87,500	53	91,800	49	96,550
13	7	40	34,250	37	38,500	33	43,950	31	48,750	-	-
14	8	33	52,750	30	58,450	27	63,400	25	66,250	-	-
15	9	47	38,140	40	41,500	35	47,650	32	54,100	-	-
16	9, 10	75	94,600	70	101,250	66	112,750	61	124,500	57	132,850
17	10	60	78,450	55	84,500	49	91,250	47	94,640	-	-
18	10, 11	81	127,150	73	143,250	66	154,600	61	161,900	-	-
19	11	36	82,500	34	94,800	30	101,700	-	-	-	-
20	12	41	48,350	37	53,250	34	59,450	32	66,800	-	-

21	13	64	85,250	60	92,600	57	99,800	53	107,500	49	113,750
22	14	58	74,250	53	79,100	50	86,700	47	91,500	42	97,400
23	15	43	66,450	41	69,800	37	75,800	33	81,400	30	88,450
24	16	66	72,500	62	78,500	58	83,700	53	89,350	49	96,400
25	17	54	66,650	50	70,100	47	74,800	43	79,500	40	86,800
26	18	84	93,500	79	102,500	73	111,250	68	119,750	62	128,500
27	20	67	78,500	60	86,450	57	89,100	56	91,500	53	94,750
28	21	66	85,000	63	89,750	60	92,500	58	96,800	54	100,500
29	22	76	92,700	71	98,500	67	104,600	64	109,900	60	115,600
30	23	34	27,500	32	29,800	29	31,750	27	33,800	26	36,200
31	19, 25	96	145,000	89	154,800	83	168,650	77	179,500	72	189,100
32	26	43	43,150	40	48,300	37	51,450	35	54,600	33	61,450
33	26	52	61,250	49	64,350	44	68,750	41	74,500	38	79,500
34	28, 30	74	89,250	71	93,800	66	99,750	62	105,100	57	114,250
35	24, 27, 29	138	183,000	126	201,500	115	238,000	103	283,750	98	297,500
36	24	54	47,500	49	50,750	42	56,800	38	62,750	33	68,250
37	31	34	22,500	32	24,100	29	26,750	27	29,800	24	31,600
38	32	51	61,250	47	65,800	44	71,250	41	76,500	38	80,400
39	33	67	81,150	61	87,600	57	92,100	52	97,450	49	102,800
40	34	41	45,250	39	48,400	36	51,200	33	54,700	31	58,200
41	35	37	17,500	31	21,200	27	26,850	23	32,300	-	-
42	36	44	36,400	41	39,750	38	42,800	32	48,300	30	50,250
43	36	75	66,800	69	71,200	63	76,400	59	81,300	54	86,200
44	37	82	102,750	76	109,500	70	127,000	66	136,800	63	146,000
45	39	59	84,750	55	91,400	51	101,300	47	126,500	43	142,750
46	39	66	94,250	63	99,500	59	108,250	55	118,500	50	136,000
47	40	54	73,500	51	78,500	47	83,600	44	88,700	41	93,400
48	42	41	36,750	39	39,800	37	43,800	34	48,500	31	53,950
49	38, 41, 44	173	267,500	159	289,700	147	312,000	138	352,500	121	397,750
50	45	101	47,800	74	61,300	63	76,800	49	91,500	-	-
51	46	83	84,600	77	93,650	72	98,500	65	104,600	61	113,200
52	47	31	23,150	28	27,600	26	29,800	24	32,750	21	35,200
53	43, 48	39	31,500	36	34,250	33	37,800	29	41,250	26	44,600
54	49	23	16,500	22	17,800	21	19,750	20	21,200	18	24,300
55	52, 53	29	23,400	27	25,250	26	26,900	24	29,400	22	32,500
56	50, 53	38	41,250	35	44,650	33	47,800	31	51,400	29	55,450
57	51, 54	41	37,800	38	41,250	35	45,600	32	49,750	30	53,400
58	52	24	12,500	22	13,600	20	15,250	18	16,800	16	19,450
59	55	27	34,600	24	37,500	22	41,250	19	46,750	17	50,750
60	56	31	28,500	29	30,500	27	33,250	25	38,000	21	43,800
61	56, 57	29	22,500	27	24,750	25	27,250	22	29,800	20	33,500
62	60	25	38,750	23	41,200	21	44,750	19	49,800	17	51,100
63	61	27	9500	26	9700	25	10,100	24	10,800	22	12,700

The schedule was optimized considering the existing and proposed methods by using Evolver engine. Evolver is an add-in optimization tool for excel that utilizes genetic algorithms for optimization. Optimization results are shown in Tables 3 and 4.

The optimization problem is defined as follows:

- The objective function: Minimize total project cost.
- Variables: Construction modes of activities.

-For traditional methods:

Variables are constrained to be only integer numbers.

The lower limit of variables is set to be “1”.

The upper limit of variables is set to be “No. of modes/activity”.

-For the proposed method

Variables are constrained to be only integer numbers.

The lower limit of variables is set to be “1”.

The upper limit of variables is set to be “Mode with minimum allowed duration”.

Table 3: Optimization results

Existing method				Proposed method							
1st and 2nd methods				3rd method							
Act ID	Selected mode (m)	Duration	Cost	TB	RB	Max. cr %	d_{all}	Selected mode (m)	Duration	Cost	
1	2	12	4,250	5	1	100%	9	3	10	5,400	
2	2	18	14,800	6	6	100%	15	1	21	11,250	
3	1	24	22,450	7	2	100%	17	3	19	27,950	
4	1	19	17800	4	0	100%	15	3	15	21,600	
5	1	28	31180	7	7	100%	21	1	28	31,180	
6	1	44	54260	9	9	100%	35	1	44	54,260	
7	1	39	47600	9	9	100%	30	1	39	47,600	
8	1	52	62140	13	5	100%	39	3	44	72,600	
9	1	63	72750	14	14	100%	49	1	63	72,750	
10	2	53	70250	16	12	100%	41	2	53	70,250	
11	1	63	83100	18	18	100%	45	1	63	83,100	
12	1	68	75500	19	19	99%	49	1	68	75,500	
13	1	40	34250	9	9	99%	31	1	40	34,250	
14	1	33	52750	8	8	99%	25	1	33	52,750	
15	1	47	38140	15	15	98%	32	1	47	38,140	
16	1	75	94600	18	18	98%	57	1	75	94,600	
17	1	60	78450	13	2	99%	47	3	49	91,250	
18	1	81	127150	20	20	98%	61	1	81	127,150	
19	1	36	82500	6	6	98%	30	1	36	82,500	
20	1	41	48350	9	9	96%	32	1	41	48,350	
21	1	64	85250	15	15	98%	49	1	64	85,250	
22	2	53	79100	16	11	98%	42	2	53	79,100	
23	1	43	66450	13	13	96%	30	1	43	66,450	
24	1	66	72500	17	17	94%	50	1	66	72,500	
25	2	50	70100	14	10	96%	40	2	50	70,100	
26	1	84	93500	22	22	92%	63	1	84	93,500	
27	1	67	78500	14	7	93%	53	2	60	86,450	
28	1	66	85000	12	12	94%	54	1	66	85,000	
29	1	76	92700	16	11	94%	60	2	71	98,500	
30	1	34	27500	8	8	92%	26	1	34	27,500	
31	1	96	145000	24	17	93%	73	2	89	154,800	
32	1	43	43150	10	10	83%	34	1	43	43,150	
33	2	49	64350	14	14	83%	40	1	52	61,250	
34	1	74	89250	17	17	88%	59	1	74	89,250	
35	2	126	201500	40	17	87%	103	3	115	238,000	
36	1	54	47500	21	21	87%	35	1	54	47,500	
37	3	29	26750	10	3	83%	25	4	27	29,800	
38	1	51	61250	13	13	77%	40	1	51	61,250	
39	1	67	81150	18	18	76%	53	1	67	81,150	
40	1	41	45250	10	10	78%	33	1	41	45,250	
41	2	31	21200	14	4	71%	27	3	27	26,850	

42	1	44	36400	14	14	80%	32	1	44	36,400
43	1	75	66800	21	21	80%	58	1	75	66,800
44	1	82	102750	19	19	79%	66	1	82	102,750
45	1	59	84750	16	16	64%	48	1	59	84,750
46	1	66	94250	16	16	64%	55	1	66	94,250
47	1	54	73500	13	13	71%	44	1	54	73,500
48	1	41	36750	10	10	74%	33	1	41	36,750
49	3	147	312000	52	26	66%	138	3	147	312,000
50	1	101	47800	52	52	52%	74	1	101	47,800
51	1	83	84600	22	22	50%	71	1	83	84,600
52	1	31	23150	10	10	61%	24	1	31	23,150
53	1	39	31500	13	13	66%	30	1	39	31,500
54	5	18	24300	5	3	33%	21	3	21	19,750
55	1	29	23400	7	7	55%	25	1	29	23,400
56	1	38	41250	9	6	26%	35	2	35	44,650
57	5	30	53400	11	8	27%	38	2	38	41,250
58	1	24	12500	8	8	55%	19	1	24	12,500
59	1	27	34600	10	10	48%	22	1	27	34,600
60	1	31	28500	10	8	17%	29	2	29	30,500
61	5	20	33500	9	7	16%	27	2	27	24,750
62	1	25	38750	8	8	8%	24	1	25	38,750
63	5	22	12700	5	4	8%	26	2	26	9,700

Table 4: Summary of the optimization results

	Existing methods 1st and 2nd methods	Proposed method 3rd method
Total Direct Cost	3,986,370	4,059,130
Total Indirect cost	2,191,000	2,184,000
Penalties	-	-
Total Cost	6,177,320	6,243,130
Total Duration	626	624

Optimization results show that the proposed method gives higher total cost in planning stage due to accounting for flexibility. Delay scenarios were randomly generated to test the performance of each scheduling method to recover delays. All project's activities were assumed to get delayed by up to 20% of their initially selected durations as per Equation (7).

$$d_{act} = (1 \text{ to } 1.2) * d_m \tag{7}$$

For the existing methods, two different corrective action plans were considered for recovery, Full horizon recovery for the 1st method and short-term recovery for the 2nd method. While the proposed method (3rd method) short-term recovery was considered for corrective actions as discussed in section 2.

Taking corrective actions to recover delays shall take place after some definite periods throughout the project as discussed in section 2. Each period was set to be every 140 days (about 22% of the total project duration) as shown in Table 5.

Table 5: Recovery periods

Period 1	0 – 140 days
Period 2	140 – 280 days
Period 3	280 – 420 days
Period 4	420 – 560 days

Schedule was optimized after each period by crashing the eligible activities to recover delays with minimum cost. Summary of optimization results for existing methods and proposed method after each period is shown in Table 6.

Table 6: Optimization results after each period

			1st Method	2nd Method	3rd Method (Proposed)
At Planning Stage		Total Direct Cost	3,986,370	3,986,370	4,059,130
		Total Indirect Cost	2,191,000	2,191,000	2,184,000
		Penalties	-	-	-
		Total Cost	6,177,370	6,177,370	6,243,130
		Duration	626	626	624
After 140 Days	Before Recovery	Delay	15	15	15
		Penalties	135,000	135,000	117,000
		Total Cost	6,364,870	6,364,870	6,412,630
		Duration	641	641	639
	After Recovery	Penalties	0	0	0
		Recovery Cost	46,900	71,600	82,900
		Total Cost	6,224,270	6,248,970	6,326,030
		Duration	607	626	626
After 280 Days	Before Recovery	Delay	18	18	18
		Penalties	0	162000	162,000
		Total Cost	6,287,270	6,473,970	6,551,030
		Duration	625	644	644
	After Recovery	Penalties	0	0	0
		Recovery Cost	-	65,650	85,600
		Total Cost	6,287,270	6,314,620	6,411,630
		Duration	625	624	625
After 420 Days	Before Recovery	Delay	21	21	21
		Penalties	180,000	171,000	180,000
		Total Cost	6,540,770	6,559,120	6,665,130
		Duration	646	645	646
	After Recovery	Penalties	180000	0	0
		Recovery Cost	n/a	54,000	89,700
		Total Cost	6,540,770	6,368,620	6,501,330
		Duration	646	624	617
After 560 Days	Before Recovery	Delay	18	18	20
		Penalties	342,000	144,000	99000
		Total Cost	6,765,770	6,575,620	6,670,330
		Duration	664	642	637
	After Recovery	Penalties	342000	144000	0
		Recovery Cost	n/a	n/a	39,250
		Total Cost	6,765,770	6,575,620	6,540,580
		Duration	664	642	622

Results shows that the proposed method has the higher cost in planning stage and after the first and the second periods, but it was able to recover delays in all periods and after the fourth period recovery the duration was 622 days which is 4 days earlier from deadline and the cost was $6,540,580. The first method results in minimum cost in the first and second periods but in the last two periods the schedule wasn't able to recover any delays and finished with duration of 664 days which is 38 days late from deadline and cost of $6,765,770. The second method was able to recover delay efficiently in the first, second, and third periods, but in the fourth period it wasn't able to recover any more delays and after the last optimization trial duration was 642 days which is 16 days delay from deadline and cost was $6,575,620.

5. CONCLUSION

As most projects are characterized by strict deadlines it is important to have schedule that can recover delays and to implement the suitable corrective action plan to maintain flexibility. This paper presents an approach to creating flexible schedule that can absorb delays whenever happens during construction. The method proposed in this paper was tested against existing methods on 63-activity case study and proved to be more efficient in recovering delays and was able to keep the project within deadline and so no penalties were applied. While the existing methods couldn't keep the project within deadline and was subjected to penalties. The total project cost considering the penalties that were applied to existing methods was less by using the proposed method. This method is more suitable for projects that are subject to penalties in case deadline was violated. While in case that a project doesn't include a penalty clause in its contract in case of delay, using the proposed method is not preferable as it results in higher cost in planning stage due to accounting for flexibility which is not required for these types of projects.

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