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Optimizing Construction Scheduling across Varying Degrees of Flexibility

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ABSTRACT

In construction project management, it is utmost important to strictly adhere to deadlines. To address this challenge, it becomes essential to have a flexible schedule that can accommodate expected delays during construction. This study delves into the impact of varying degrees of flexibility on overall project outcomes. Flexibility in scheduling was modelled as a function of the activities' unused modes of construction. The proposed approach integrates flexibility into schedule optimization during the planning phase, with the flexibility degree denoted as "n." As "n" increases, flexibility decreases, allowing for more crashing options (i.e., expedited construction). Drawing from existing literature, a case study was considered to explore the relationship between the flexibility degree and schedule outcomes, represented in five scenarios. Results reveal that implementing this approach ensures project activities maintain residual flexibility as the project progresses. However, it also leads to higher cost estimates during the planning stage. Conversely, opting for a low value of "n" significantly restricts compression options for activities during planning, resulting in higher total project cost estimates. In extreme scenarios (e.g., Scenario #5), selecting a low "n" value could even cause the project duration to exceed the deadline. Ultimately, the optimal choice of the flexibility degree "n" relies on the unique conditions and requirements of each project. Balancing time, cost, and flexibility becomes critical to mitigate the risk of failing to meet project constraints and enhance the schedule's ability to absorb unforeseen challenges causing delay during construction.

1. Introduction

Project scheduling is a fundamental aspect of construction project management, serving as the blueprint for the timely and efficient completion of tasks and goals within a project. It involves the strategic allocation of resources, time, and effort to ensure that project objectives are met within the specified timeframe and budget. In project scheduling, optimizing the schedule often involves considering the trade-offs between time, cost, and or resources. Time-cost trade-off analysis, also known as crashing or expedited scheduling, is a technique used to determine the most cost-effective way to accelerate project completion without compromising quality.

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1.1 Previous Research

Numerous models have been developed to solve the time cost tradeoff problem (TCTP) since it was first presented by Kelley and Walker in 1959 [1]. These models can be classified into three main groups: Heuristic approaches, Mathematical models, and Evolutionary Algorithms. Examples of heuristic approaches include Siemens's effective cost slope model [2], and Moselhi's structural stiffness method [3]. Typically, mathematical models utilize linear programming, integer programming, or dynamic programming. Meyer and Shaffer [4] used integer programming to solve time-cost problems considering both linear and discrete relationships within the same activity. Burns *et al.*, [5] used a combination of linear programming and integer programming 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 behaviour of species as stated by Elbeltagi *et al.*, [6]. Hegazy [7] developed a genetic algorithm procedure to provide an optimization model for TCT analysis. Zheng *et al.*, [8] presented a multi-objective approach that optimizes the total time and total cost of a construction project simultaneously utilizing genetic algorithms. Elbeltagi *et al.*, [6] made a comparative study of five different evolutionary algorithms to optimize a construction TCTP. Aminbakhsh and Sonmez [9] developed a discrete particle swarm optimization model to optimize large-scale construction TCTP in a short time.

Many efforts have been made to consider practical and real-life factors on schedule optimization to produce more practical schedules as these factors practically have a high impact on project outcomes. Menesi *et al.*, [10] considered various constraints in TCT, including stringent deadlines and resource limitations. They employ constraint programming (CP) as a mathematical optimization technique to simultaneously resolve resource-constraint scheduling (RCS) and TCT. Mahmoudi and Feylizadeh [11] formulated a mathematical model that considers risk and quality considerations in project crashing, aiming to minimize total project costs while mitigating practical risks and maintaining quality standards. Milat *et al.*, [12] solved the Resource-Constrained Project Scheduling Problem (RCPSP) with two objectives: minimizing project duration and enhancing the resilience of the baseline schedule. Their study focused on maximizing free floats for early activities in the schedule to enhance resilience. Other models have been developed by several authors [13-15] for fast-track construction projects in which an overlapping of activities approach is followed. This study aims to investigate the impact of varying the degrees of flexibility on overall project outcomes, as a step to balance it with time and cost to enhance the schedule's ability to absorb unforeseen challenges causing delay during construction.

1.2 Schedule Flexibility

Construction projects often encounter challenges and delays during execution, impacting project completion times. Time delays and cost overruns are among the most common phenomena in the construction industry [16,17]. Traditional scheduling approaches do not adequately account for these inevitable delays, leading to suboptimal scheduling models. Few researchers proposed integrating delay recovery into the generation of an optimal construction schedule. The process of delay recovery involves strategically managing remaining and incomplete activities to minimize project delays through a series of consecutive corrective measures during the construction. In such scenarios, project crashing will be the key to adhering to deadlines and avoiding penalties. Crashing requires the allocation of additional resources to specific activities to be shortened or by changing the method used for faster construction methods, which correspondingly increases their direct costs.

The term “schedule flexibility” refers to the eligibility of project activities to be crashed over the life of the project as corrective action to recover delays and keep the project within the deadline. Traditionally, optimum schedule generation does not consider schedule flexibility which results in unpractical schedules. Recently, the approach for flexible scheduling has gained researchers’ attention. Hegazy and Abuwarda [18] introduced the concept of residual flexibility, defining schedule flexibility as the capacity of a schedule to accommodate further corrective measures. They conducted a study aimed at measuring the residual flexibility of any proposed corrective action plan, concluding that recovering delays in the short term incurs higher costs but provides greater flexibility for the remaining duration of the project. Conversely, recovering delays over the full horizon may be less costly but results in less flexibility for the project's remainder. However, if the original project plan doesn’t have flexibility for the activities at the end of the project, it will most likely get delayed no matter what the corrective action plan is. Turkoglu *et al.*, [19] have considered flexibility by assigning a crash duration consumption rate to individual activities, whereby the maximum crash duration of each activity is multiplied by a factor ranging from 0% to 100%, determined by the planner's estimation. While this study endeavours to enhance flexibility in project scheduling, the approach of assigning crash duration consumption rates to each activity is done independently based on the planner's estimation lacking a systematic method for achieving a flexible project schedule.

1.3 Problem Background

Belal and Elhakeem [20] have introduced an approach to flexible scheduling by ensuring that all activities have sufficient ability to crash during construction. Their approach involves incorporating flexibility to schedule optimization in the planning stage by constraining the selection of construction modes “Minimum allowed duration” where it is not allowed to select a construction mode having a duration less than “Minimum allowed duration”. Determining the value will of “Minimum allowed duration” is done by assigning the factor “Maximum crash %” for each activity. The “Maximum crash %” varies according to the start times of activities so that activities that start later in the project will have a lower “Maximum crash %” to allow for flexibility as the project goes on. Explanations for these factors are presented below.

Each activity has various construction modes, each varies in cost and duration. The difference in duration 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 Eq. (1)

$$\mathrm{TB}_{\mathrm{i}} = \mathrm{d}_{\mathrm{max.\ i}} - \mathrm{d}_{\mathrm{min.\ i}} \tag{1}$$

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.

Time cost tradeoff optimization involves selecting the construction mode for each activity to achieve an optimal total project cost and/or duration. The difference in duration between the selected mode and the mode with the minimum duration is represented by the term “Remaining crashing buffer” as shown in Eq. (2). This term was introduced to measure the capability of each activity to be compressed at any given time during construction.

$$\mathrm{RB}_{\mathrm{i}} = \mathrm{d}_{\mathrm{n\ i}} - \mathrm{d}_{\mathrm{min.\ i}} \tag{2}$$

where,

RB_i is the remaining crashing buffer of activity i.

$d_{n\,i}$ is the duration of the selected mode of activity i.

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

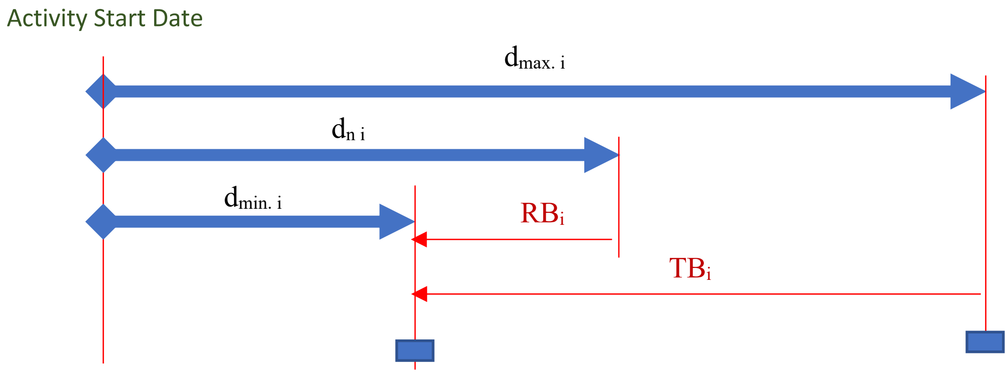

Fig. 1. Total crashing buffer and remaining crashing buffer of an activity

The residual flexibility in this study is considered to be a function of the activity's unused modes of construction. Incorporating flexibility into time cost tradeoff optimization involves controlling the compression of activities during optimization. This control allows activities starting earlier in the schedule to be compressed to a higher extent compared to those starting later, fostering flexibility throughout the project's progression. Therefore, the compression of activities during time-cost tradeoff optimization is restricted by the start times of activities relative to the overall project duration, utilizing the "Minimum allowed durations" factor. This factor ensures that each activity's duration during schedule optimization does not fall below the specified "Minimum allowed durations," as determined by Eq. (3).

$$d_{all.\ i} = d_{max.\ i} - (TB * Max.cr\,\%_{\,i}) \tag{3}$$

where,

$d_{all.\,i}$ is the minimum allowed duration of activity i.

Max. cr % $_i$ is the maximum crash percentage of activity i.

The "Max. cr %" parameter establishes the minimum level of remaining flexibility for each activity, with lower values indicating greater residual flexibility. To optimize the schedule, prioritizing more residual flexibility for activities starting later, the "Max cr. %" is suggested to be dependent on the start times of activities, as outlined in Eq. (4).

$$Max.cr\,\%_{\,i} = 1 - \left(\frac{ES_i}{TD}\right)^n \tag{4}$$

where,

ES_i is the early start time of activity i.

TD is the total project duration.

n is the flexibility degree.

The early start time of activities is chosen over the late start times to allow the non-critical activities to be compressed to a higher degree to provide more crashing options. Raising the degree of the term $(\frac{ES}{TD})$ to "n" flexibility 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. And 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 flexibility degrees "n".

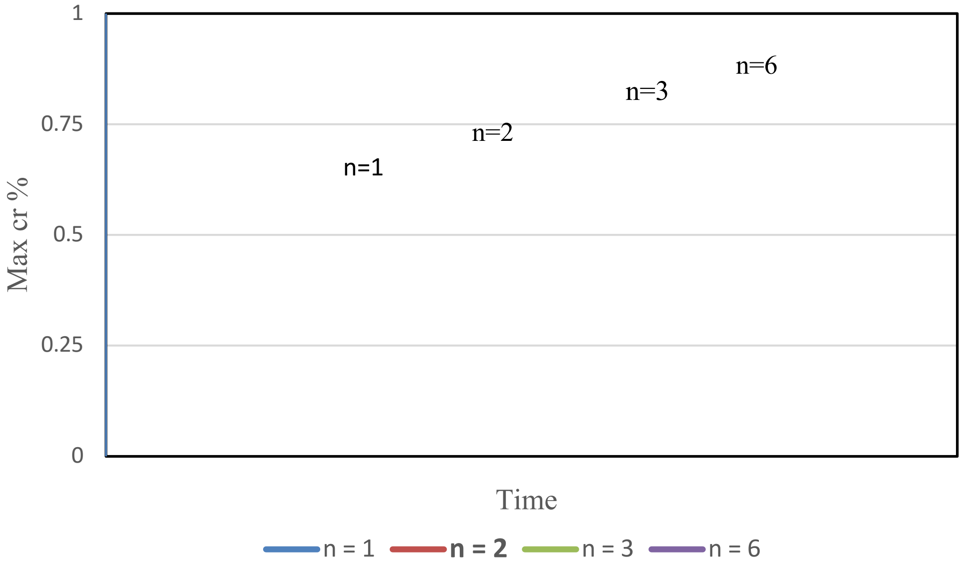

Fig. 2. Early start time and Max cr % of activities considering different degrees

In the research presented by Belal and Elhakeem [20] they experimented with the method proposed in a case study but only considered degree of flexibility (n=2) and did not show how choosing different degrees of flexibility may affect the overall project outcomes. The objective of this research is to study how changing flexibility degrees affects the total project cost, duration and residual flexibility as an important step for schedule optimality.

2. Research Methodology

To study the project outcomes across different degrees of flexibility, a case study adapted from Turkoglu *et al.*, [19] is used, where the model is created as follows.

1. A spreadsheet is prepared using Microsoft Excel with all CPM calculations and TCT/crashing capabilities.
2. The developed spreadsheet can calculate the flexibility measures considered in this study "Total crashing buffer, Remaining crashing buffer, Maximum crash percentage, Minimum allowed durations" for each activity according to the specified "n".
3. An advanced optimization engine "Evolver" that utilizes genetic algorithms (GAs) is used to optimize the schedule considering five different scenarios,
    - The first scenario is the traditional optimization without considering any flexibility measures.
    - Flexibility measures are considered in the other four scenarios; each scenario has different flexibility degree ranging from "n = 4" to "n = 1"

<u>The optimization problem is defined as follows:</u>

- **The objective function:** Minimize total project cost.
- **Variables:** Duration of activities throughout selecting the construction mode.

- Variables are constrained to be only integer numbers.
- The lower limit of variables is set to be “$d_{min\,i}$” for scenario 1 and “$d_{all\,i}$” for other scenarios.
- The upper limit of variables is set to be “$d_{max\,i}$”.

Where,

$d_{max.\,i}$ is the maximum duration of activity i.
$d_{min.\,i}$ is the minimum duration of activity i.
$d_{all.\,i}$ is the minimum allowed duration of activity i.

3. Case Study Results

The case study comprises of network of 14 activities. Inputs for the case study are presented in Table 1. The contract duration is considered 540 days, the daily penalty cost is $30,000, the daily early finish bonus is $6,000, and the daily indirect cost is $5,000. Table 2 shows the parameters considered for each scenario.

Table 1
Case study data

	Independent		Dependents			Durations and crash cost				
			D1	D2	D3					
ID	Start	End	ID	ID	ID	Normal Dur (d max)	Maximum crash duration	Minimum Duration (d min)	Normal Cost	Crash Cost/day
1	0					66	9	57	732,600	8,880
2			1			50	12	38	435,000	6,960
3			1			136	16	120	1,101,600	6,480
4			1			142	56	86	1,384,500	7,800
5			2	3		130	24	106	1,300,000	8,000
6			3	4		138	28	110	1,711,200	9,920
7			4			140	36	104	1,344,000	7,680
8			4			56	6	50	638,400	9,120
9			5	6	7	54	12	42	496,800	7,360
10			6			60	12	48	570,000	7,600
11			6	7		100	36	64	945,000	7,560
12			8			128	48	80	1,190,400	7,440
13			9	10		108	14	94	939,600	6,960
14			11	12	13	88	14	74	818,400	7,440

Table 2
Parameters considered for each scenario

	Scenario #1	Scenario #2	Scenario #3	Scenario #4	Scenario #5
Variables	Duration of activities. ○ “$d_{min\,i}$” lower limit ○ “$d_{max\,i}$” upper limit.	Duration of activities. ○ “$d_{all\,i}$” lower limit ○ “$d_{max\,i}$” upper limit.	Duration of activities. ○ “$d_{all\,i}$” lower limit ○ “$d_{max\,i}$” upper limit.	Duration of activities. ○ “$d_{all\,i}$” lower limit ○ “$d_{max\,i}$” upper limit.	Duration of activities. ○ “$d_{all\,i}$” lower limit ○ “$d_{max\,i}$” upper limit.
Flexibility degree (n)	n/a	4	3	2	1

After performing optimization for each of the scenarios above, the results of time, cost, and flexibility are highlighted in Figure 3 through Figure 7. In each Figure, the selected duration for each activity is shown and the corresponding direct cost to the selected duration. Also, the remaining crashing buffer is shown for each activity and a diagram showing the average remaining crashing buffer for activities along the project life span. The diagram is plotted by adding the sum of the remaining buffers for ongoing activities at a certain time and dividing the resulting value by the number of activities ongoing at that time to get the average crashing buffer.

Scenario #1 (Traditional optimization without flexibility consideration):

Optimization results show that from day 420 till the end of the project (day 540), there is no residual flexibility for the remaining activities. This indicates that any delay that occurs during the last 120 days of the project cannot be recovered and most likely the project will get delayed. Consequently, penalties will be incurred resulting in a much higher cost than the cost estimated at the planning stage, Figure 3.

Activity ID	Selected Duration (Days)	Cost ($)	Remaining Crashing Buffer "RB" (Days)
1	57	812,520	0
2	50	435,000	12
3	120	1,205,280	0
4	120	1,556,100	34
5	130	1,300,000	24
6	138	1,711,200	28
7	140	1,344,000	36
8	56	638,400	6
9	50	526,240	8
10	52	630,800	4
11	100	945,000	36
12	128	1,190,400	48
13	94	1,037,040	0
14	74	922,560	0
Total Project Duration (Days)			540
Penalities incurred ($)			-
Bonus ($)			-
Total Project Cost ($)			16,954,540

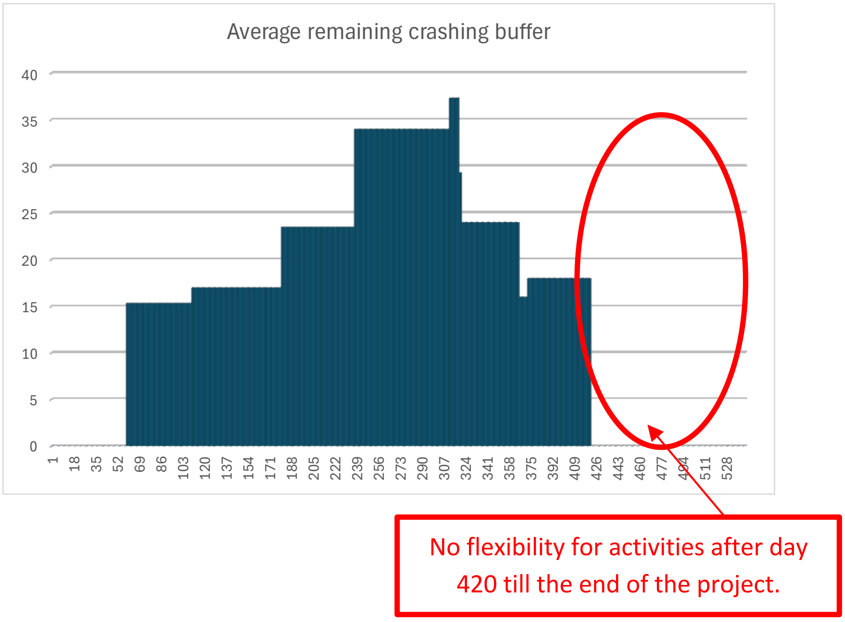

Fig. 3. Scenario #1 Optimization results

Scenario #2 (Flexibility degree n = 4):

Optimization results show that after considering flexibility measures and assigning a minimum allowed duration for each activity during optimization, the activities after day 420 that previously had no residual flexibility in Scenario#1 have now residual flexibilities of an average 2 to 7 days which can be used to recover unexpected delays. On the other hand, the total project cost has increased in Scenario #2 compared to Scenario #1 where the cost has increased from 16,954,540 to 17,041,380 (about 0.5% increase). This increase in the estimated total cost in the planning stage is expected as there is an additional parameter considered in optimization. However, scenario #2 is more practical and more capable of keeping the project within the deadline and avoiding penalties. So, deviation from planned in Scenario #2 is expected to occur with a lower impact on the total project outcomes compared to Scenario #1, Figure 4.

Activity ID	Selected Duration (Days)	Cost ($)	Remaining Crashing Buffer "RB" (Days)
1	57	812,520	0
2	50	435,000	12
3	121	1,198,800	1
4	121	1,548,300	35
5	130	1,300,000	24
6	131	1,780,640	21
7	136	1,374,720	32
8	56	638,400	6
9	44	570,400	2
10	49	653,600	1
11	100	945,000	36
12	128	1,190,400	48
13	96	1,023,120	2
14	81	870,480	7
Total Project Duration (Days)			540
Penalities incurred ($)			-
Bonus ($)			-
Total Project Cost ($)			17,041,380

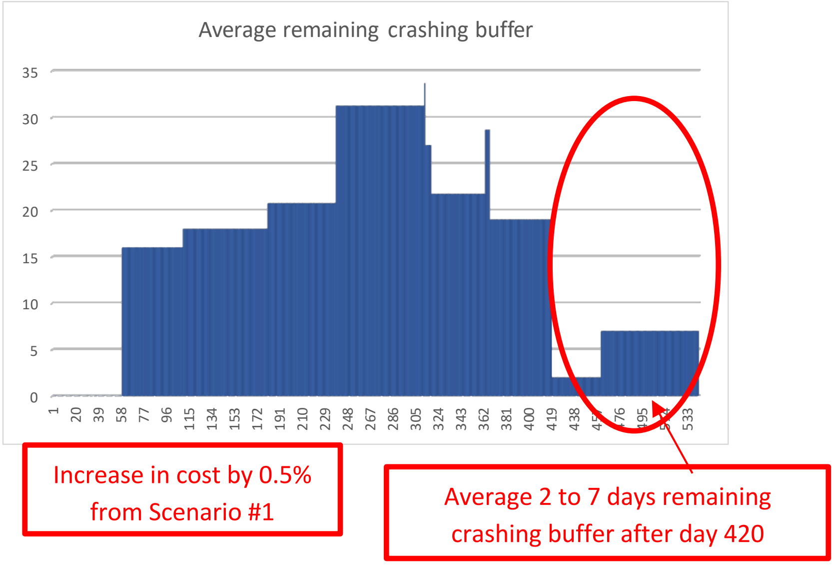

Fig. 4. Scenario #2 Optimization results

Scenario #3 (Flexibility degree n = 3):

Optimization results show that by increasing the degree of flexibility the residual flexibility for activities increases as the project progresses. This can be seen after day 420 the average residual flexibility has increased from (2 to 7 days) in Scenario #2 to (4 to 8 days) in Scenario #3. And on the other hand, there is a slight increase in the project's total cost (only a 0.2% increase), Figure 5.

Activity ID	Selected Duration (Days)	Cost ($)	Remaining Crashing Buffer "RB" (Days)
1	57	812,520	0
2	50	435,000	12
3	120	1,205,280	0
4	117	1,579,500	31
5	130	1,300,000	24
6	128	1,810,400	18
7	137	1,367,040	33
8	56	638,400	6
9	44	570,400	2
10	50	646,000	2
11	100	945,000	36
12	128	1,190,400	48
13	98	1,009,200	4
14	82	863,040	8
Total Project Duration (Days)			540
Penalities incurred ($)			-
Bonus ($)			-
Total Project Cost ($)			17,072,180

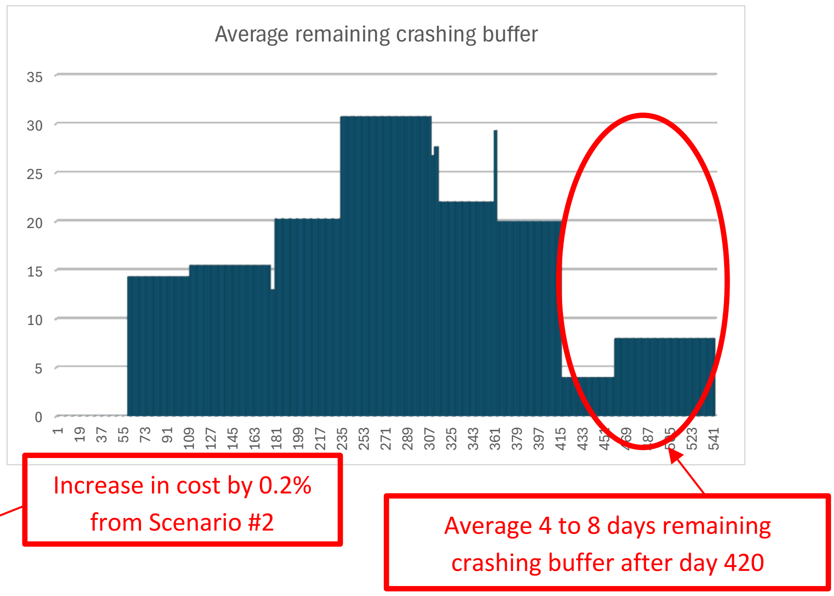

Fig. 5. Scenario #3 Optimization results

Scenario #4 (Flexibility degree n = 2):

Similarly, optimization results show more residual flexibility for the schedule with an increase in the total project cost, Figure 6.

Activity ID	Selected Duration (Days)	Cost ($)	Remaining Crashing Buffer "RB" (Days)
1	57	812,520	0
2	50	435,000	12
3	120	1,205,280	0
4	120	1,556,100	34
5	129	1,308,000	23
6	123	1,860,000	13
7	129	1,428,480	25
8	56	638,400	6
9	45	563,040	3
10	51	638,400	3
11	100	945,000	36
12	128	1,190,400	48
13	100	995,280	6
14	84	848,160	10
Total Project Duration (Days)			540
Penalities incurred ($)			-
Bonus ($)			-
Total Project Cost ($)			17,124,060

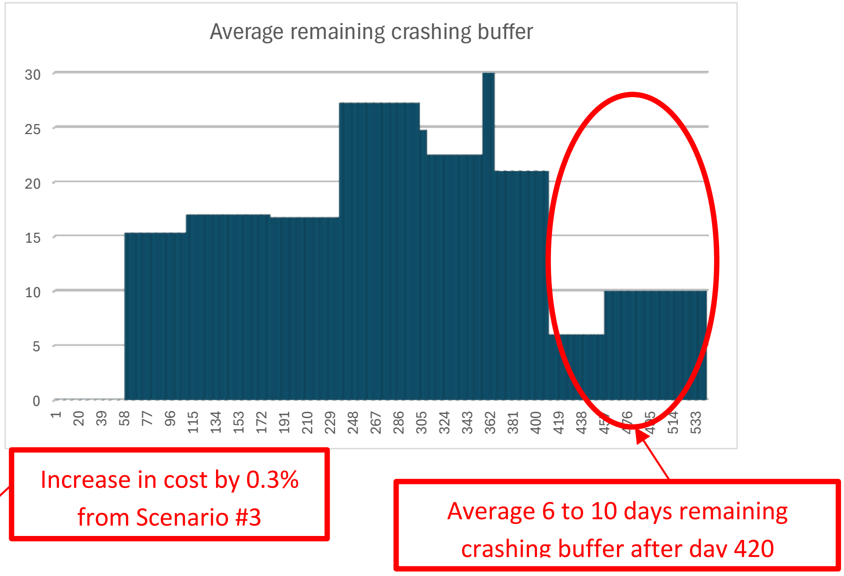

Fig. 6. Scenario #4 Optimization results

Scenario #5 (Flexibility degree n = 1):

In this Scenario, the project has surpassed its deadline, resulting in penalties that will be added to the overall project cost. This outcome was influenced by opting for a low value of "n" (in this case n=1), which significantly restricted the available options for schedule compression during optimization. Consequently, the total project duration couldn't be reduced below 549 days, excessively prioritizing schedule flexibility, Figure 7.

Activity ID	Selected Duration (Days)	Cost ($)	Remaining Crashing Buffer "RB" (Days)
1	57	812,520	0
2	50	435,000	12
3	121	1,198,800	1
4	121	1,548,300	35
5	130	1,300,000	24
6	123	1,860,000	13
7	130	1,420,800	26
8	56	638,400	6
9	48	540,960	6
10	55	608,000	7
11	100	945,000	36
12	128	1,190,400	48
13	103	974,400	9
14	85	840,720	11
Total Project Duration (Days)			549
Penalities incurred ($)			270,000.00
Bonus ($)			-
Total Project Cost ($)			17,328,300

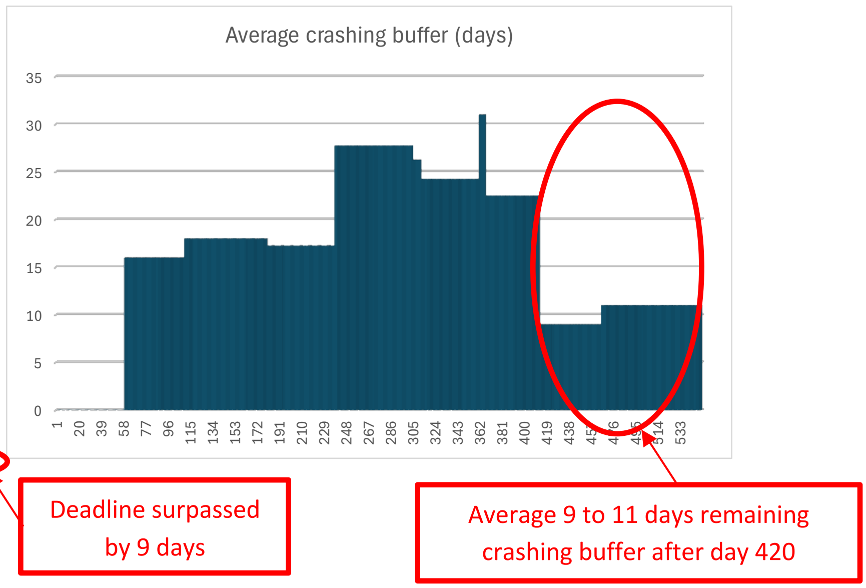

Fig. 7. Scenario #5 Optimization results

4. Concluding Remarks

As most projects are characterized by strict deadlines, it is important to have a flexible schedule that can recover expected delays. This research studies the effect of selecting different degrees of flexibility on the overall project outcomes. It is concluded that flexibility in scheduling is considered a function of the activity's unused modes of construction. A well-defined approach was proposed to incorporate flexibility to schedule optimization in the planning stage. The flexibility degree “n” sets the desirable flexibility for the project. As the value of “n” increases the degree of flexibility decreases and more crashing options become available for activities in the planning stage. The results from the case study show that utilizing the proposed approach ensures that project activities have residual flexibility as the project progresses but result in higher cost estimates in the planning stage. Also, using a low value of “n” has been noticed to severely limit the compression options for the activities in the planning stage and results in a much higher estimate of the total project cost. In some cases, as shown in Scenario #5 opting for a low value for “n” could result in a project duration surpassing the deadline. Therefore, the optimal selection of the degree "n" will be influenced by the unique conditions and requirements of each project. Finding the optimal balance between time, cost and flexibility can reduce the risk of failing to meet project constraints and enhance the schedule's capacity to absorb further execution challenges.

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