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SCHEDULE FLEXIBILITY AND COMPRESSION HORIZON: NEW KEY PARAMETERS FOR EFFECTIVE CORRECTIVE ACTIONS

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Abstract: To meet strict project deadlines, practitioners are frequently faced with situations that require effective corrective actions such as speeding up some construction tasks. As corrective actions are necessary to accommodate the inevitable delays, the ability to do further actions becomes dependent on the capacity of the schedule to accommodate further actions of the schedule. This paper, thus, introduces a new concept “Schedule Flexibility” that refers to the residual capacity of an initial or interim schedule as a function of: (1) the activities’ unused modes of construction; (2) the activities’ unused crashing options; and (3) the activities’ remaining total floats. For practicality, schedule flexibility takes into account the preference in having the corrective action implemented on a short-term or a long-term compression horizon of the project. As such, both the schedule flexibility and the compression horizon become two important parameters that govern corrective action plans. These two parameters are often overlooked in the typical focus on time and cost in schedule compression. A case study project with alternative corrective actions was used to examine the relationship between compression horizon and the schedule flexibility. The case study showed that time, cost, and schedule flexibility can identify the optimum compression plan and its horizon, to correct schedule defaults without exhausting the project’s residual flexibility.

1 INTRODUCTION

Construction projects experience many changes that often cause time and cost deviations. Therefore, frequent schedule updating, corrective action planning, and schedule compression, are essential tasks for keeping projects within deadlines and resource constraints. In the literature, project expedition has often been referred to as schedule acceleration or compression, which can be carried out using variety of time-cost trade-off (TCT) techniques, such as activity linear crashing (e.g., Siemens 1971; Elmeghraby and Salem 1981; Hajdu 1996; Feng et al. 1997; Li and Love 1997; Hegazy 1999) and discrete mode-substitution (Demeulemeester and Herroelen 2002; Peteghem and Vanhoucke 2010; Menesi et al. 2013; Menesi and Hegazy 2014; Abuwarda and Hegazy 2016). Crashing involves adding extra resources to linearly reduce the duration of some activities (mainly critical ones) at the expense of extra direct cost. Activity mode substitution, on the other hand, involves selecting among execution alternatives (ranging from cheap and slow to fast and expensive modes) for each activity.

In all the research efforts related to schedule compression, two underlying assumptions are inherently used and can result in unpractical schedules: (1) all activities in the schedule have equal eligibility to be compressed; and (2) project time and cost are the only two metrics that define the quality of a compressed schedule. With respect to the first assumption, equal activity eligibility assumes the project manager is indifferent about the desired period within which to recover delays (referred to in this paper as the compression horizon) and whether this horizon is preferred to be on the short-term, the long-term, or both. In addition, same activity priority overlooks the fact that some activities cannot be compressed if pre-committed contractually to a certain duration and start time.

With respect to the second assumption, time and cost alone are not sufficient as practical indicators of the quality of schedule compression decisions. For example, crashing the last activity in a long schedule (i.e., the compression horizon focuses on the long-term), for example, can be justified because it is cheap, but can only realize the time savings at the very end of the project, which may not be desirable. More importantly, it exhausts the long-term ability of the schedule to absorb future delays. As another example, suggesting an aggressively compressed plan in which all activities are critical represents high risk to the project, particularly if the project is still in its early stage. These examples, thus, highlight the absence of a metric to quantify the residual flexibility of corrective action schedules.

Based on the above discussion, a fine trade-off is needed between schedule compression decisions (including the compression horizon) that can recover the violations in project constraints, yet without exhausting the schedule’s ability to accommodate future delays. To enable this trade-off, two important aspects are analyzed in the paper to understand their effect on schedule compression: the compression horizon; and the residual flexibility of a schedule. Schedule flexibility in this paper is defined as the ability of the schedule to accommodate further corrective actions. This concept becomes an important objective to be measured and quantified during corrective-action planning.

2 COMPRESSION HORIZON AND SCHEDULE FLEXIBILITY

2.1 Compression Horizon

Fast recovery from deviations is an important sign of good management, and requires a short-term compression horizon for corrective actions. On the one hand, a short-term horizon (as in cases 1 and 2 in Figure 1) leaves long-term activities intact and is able to absorb future deviations, but is costly and disrupts short-term activities with little warning. On the other hand, a horizon focused on long-term only (case 3 in Figure 1) does not recommend actions on a short notice, but seriously exhausts the ability to absorb future deviations. A full horizon (Case 4, which is typically followed in all research efforts) offers the widest compression options, has less compression cost, but can easily exhausts long-term flexibility too. Once a compression horizon is decided, the activities within this horizon become eligible for crashing (as indicated on the right side of Figure 1).

In the literature, defining decision horizon is often discussed in the manufacturing domain. Some interesting efforts (e.g., Ghoniem 2002; Chong 2012) discussed the rolling horizon strategy, which is a dynamic process to determine the shortest horizon needed to recover from defaults. Such a concept is useful to apply to schedule compression. It is also possible to define the short-term horizon and the long-term horizon in terms of a number of reporting periods, however, the durations of the long-term and short-term horizons are project-specific.

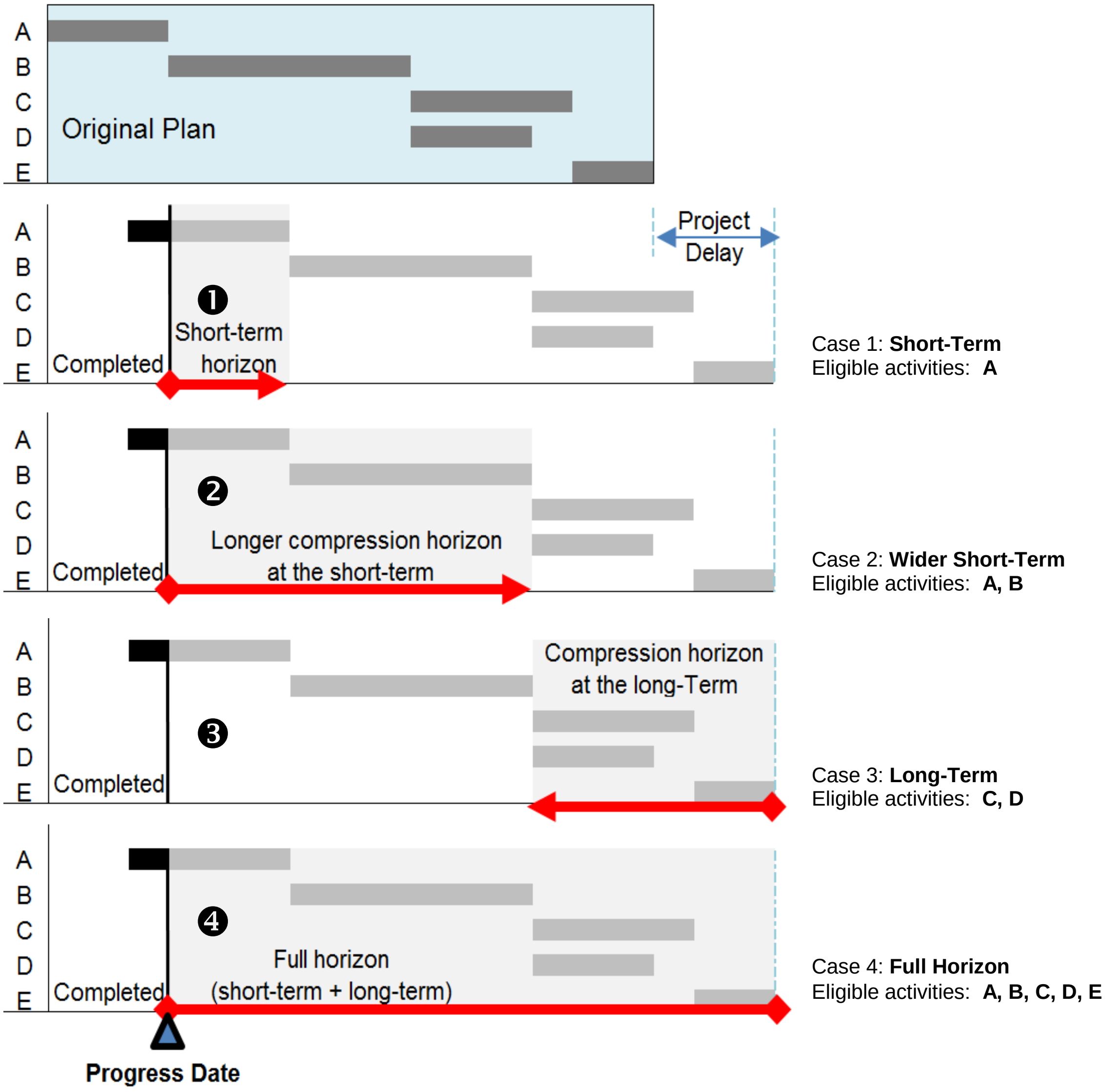


Figure 1: Compression horizons: Short-Term, Long-Term, or Full

2.2 Schedule Flexibility

Because schedule compression and corrective actions involve crashing some activities and re-arranging others, it consumes a portion of the schedule flexibility. Typically, researchers consider activities' total floats to represent a primary flexibility in the construction schedule, which can be used for resource leveling and other schedule improvements. De La Garza et al. (1991), for example, dealt with the total float of each activity as a commodity that can be traded between the owner and the contractor based on the assumption that any loss in total float has to be replaced with monetary contingency. Schedule compression efforts also utilize the activities' optional execution modes and/or the linear time-cost function between normal and crash points, as flexible options for compression decisions. In this regard, Moselhi (1993) drew an analogy between activities' crashing capacity and "spring stiffness" in an interesting research that dealt with time-cost trade-off analysis as a structural analysis problem. No efforts, however, provided a formal representation of schedule flexibility.

Regardless of the compression horizons used to determine various corrective actions, Schedule Flexibility is calculated from a specific time period on the schedule, as shown on Figure 2. The figure shows the first part of the schedule being the already completed portion of the work done so far, ending with the current progress date, and this period is not used in the calculation. The second part of the schedule is a period of time in which no changes are expected or allowed to the plan (depending on how frequent the plan is revisited for another corrective action), and this period is not used in the calculation. A special case of the calculation is for the schedule before start of construction, where the actual progress portion and the fixed portion do not exist, and thus the whole schedule is used in the calculation. Accordingly, schedule flexibility is calculated considering the activities that lie after the fixed period, which can be grouped in different ways: either as two parts (short-term, and long-term, as indicated on Figure 2); or as multiple parts that relate to each reporting period.

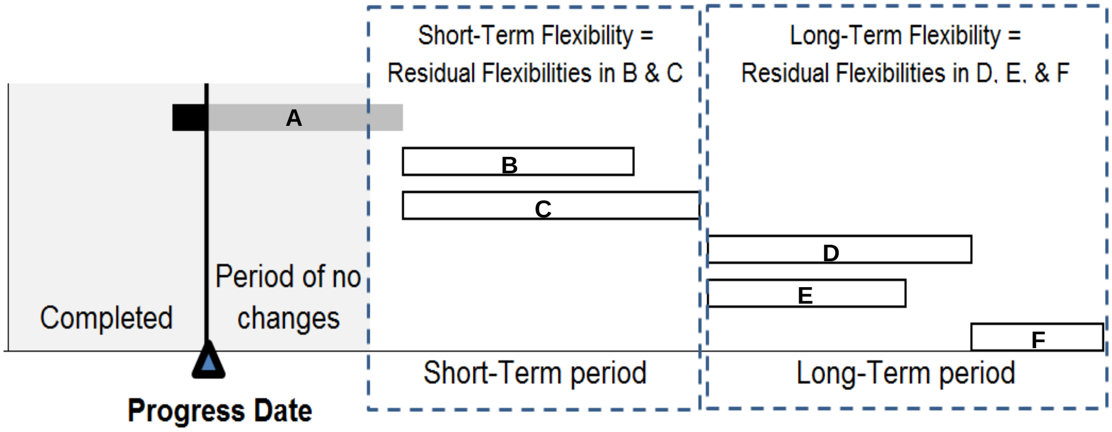
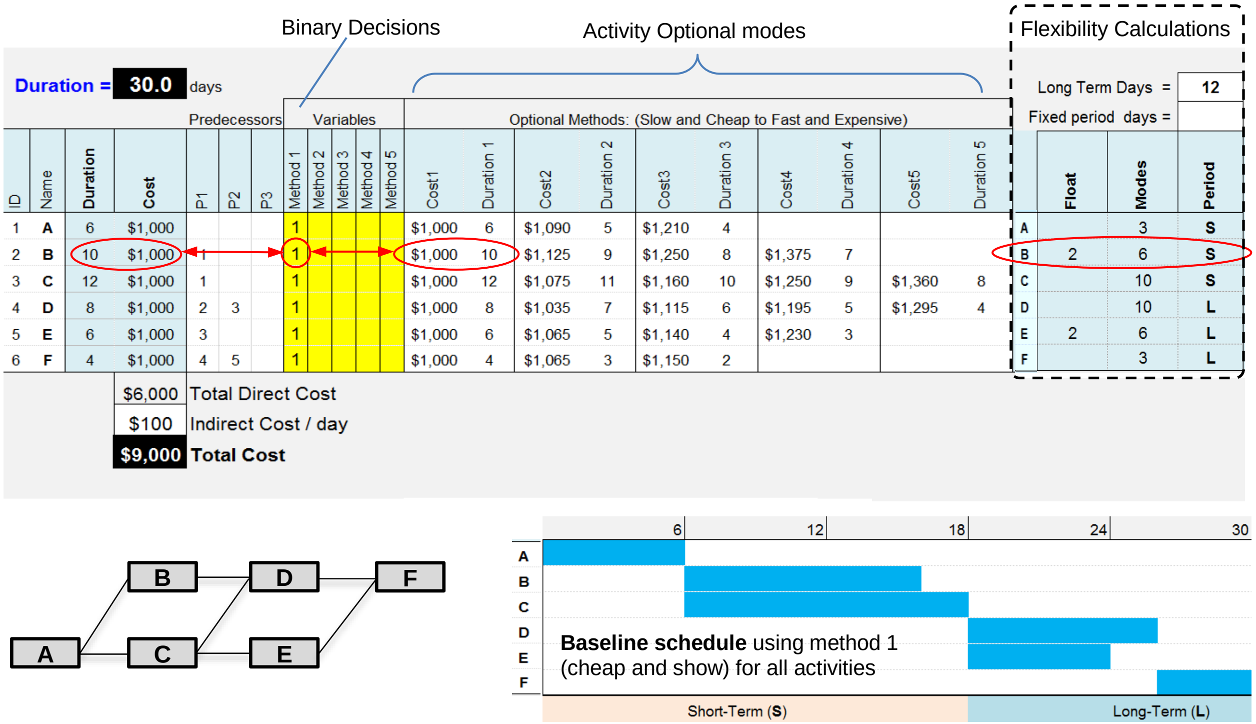


Figure 2: Periods for calculating schedule flexibility

Schedule flexibility quantifies the residual flexibility of an initial or interim schedule. Short-term and long-term flexibilities are proposed to be functions of: (1) activities' current total floats (ability to handle resource issues); (2) the residual crashing ability of activities; and (3) the activities' beneficial unused modes of construction.

3 CASE STUDY EXAMPLE

To demonstrate the proposed Schedule Flexibility concept and use, a small case study is presented after being implemented in a spreadsheet with CPM calculations, as shown in Figure 3. The figure shows each activity has up to 5 optional activity modes (sorted from cheap and slow to fast and expensive), and shows the network diagram of all activity relations. The baseline schedule was first obtained (with each activity using its cheapest mode, Method 1), as specified in the binary variable columns on the figure, with 30 days project duration and a total cost of $9,000. Before start of construction, all the schedule is flexible for changes, thus, with a long-term (L) period being set to 12 days (from end), the first 18 days form the short-term (S) period, as shown at the bottom of the baseline chart.



Duration = 30.0 days

Long Term Days = **12**
Fixed period days =

				Predecessors			Variables					Optional Methods: (Slow and Cheap to Fast and Expensive)													
ID	Name	**Duration**	**Cost**	P1	P2	P3	Method 1	Method 2	Method 3	Method 4	Method 5	Cost1	Duration 1	Cost2	Duration 2	Cost3	Duration 3	Cost4	Duration 4	Cost5	Duration 5		**Float**	**Modes**	**Period**
1	**A**	6	$1,000				1					$1,000	6	$1,090	5	$1,210	4					**A**		3	**S**
2	**B**	10	$1,000	1			1					$1,000	10	$1,125	9	$1,250	8	$1,375	7			**B**	2	6	**S**
3	**C**	12	$1,000	1			1					$1,000	12	$1,075	11	$1,160	10	$1,250	9	$1,360	8	**C**		10	**S**
4	**D**	8	$1,000	2	3		1					$1,000	8	$1,035	7	$1,115	6	$1,195	5	$1,295	4	**D**		10	**L**
5	**E**	6	$1,000	3			1					$1,000	6	$1,065	5	$1,140	4	$1,230	3			**E**	2	6	**L**
6	**F**	4	$1,000	4	5		1					$1,000	4	$1,065	3	$1,150	2					**F**		3	**L**

$6,000 Total Direct Cost
$100 Indirect Cost / day
$9,000 Total Cost

Baseline schedule using method 1 (cheap and show) for all activities

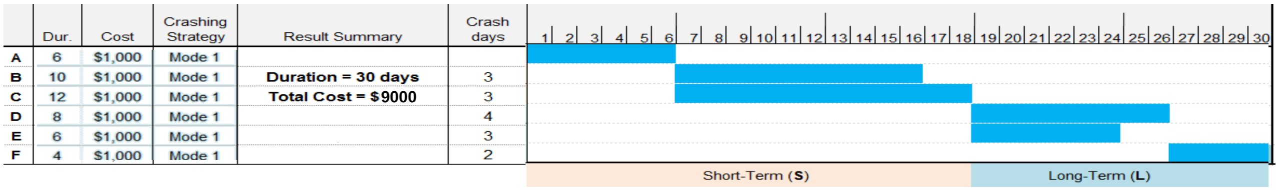
Figure 3: Case study data and baseline schedule

On the right side of Figure 3, the three columns are showing: activity flexibility due to float; activity flexibility due to modes; and activity period type (short-term or long-term). Considering activity B, for example, it has 2 days float and 4 modes. Because it currently uses mode1 (10 days), it has flexibility to be crashed to mode2 (saving 1 day), or to mode3 (saving 2 days), or to mode4 (saving 3 days). Therefore, its mode flexibility is the sum of the savings (1 + 2 + 3 = 6) as indicated on Figure 3. The activity also lies in the short-term (S) period as its start is within that period, as shown on the baseline schedule. It is important to note that although the maximum compression of activity B is 3 days (from mode 1 to mode 4 directly), adding the flexibilities of all the modes makes sense as the intent is to measure the overall flexibility, not just the maximum compressibility of the activities.

4 Relationship between Compression Horizon and flexibility

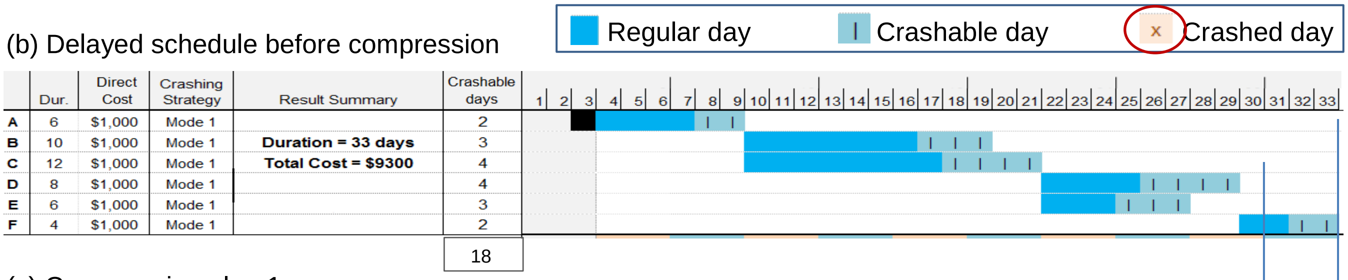
Using the same case study, several experiments were conducted to crash the project using different compression horizons, and accordingly analyze the relationship with flexibility. The baseline schedule is shown in Figure 4a with its decisions where all activities are using mode (1). During execution, the project is assumed to be delayed for two days and did minor progress in the third day, thus, the current progress date is day 3 and the project is expected to be delayed till day 33 (Figure 4b). With a reporting period every 3 days, the project is being analyzed for correction action (compression) planning to bring it back to its original deadline of 30 days. Any compression plan will remain unchanged for at least one reporting period, thus, the fixed period (as discussed before in Figure 2) is 3 days. Given this information, five alternative compression plans were generated with compression horizons of 10, 15, 20, 27, and 30 days, respectively, as shown in Figure 4c, 4d, 4e, 4f and 4g. A summary of the results is also shown in Table 1.

(a) Baseline Schedule (No compression)



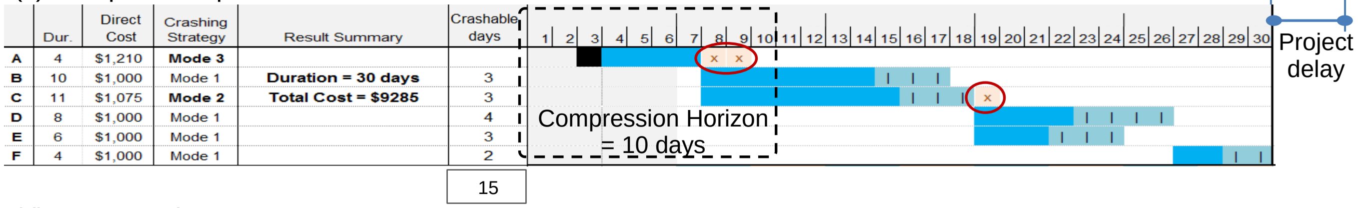
	Dur.	Cost	Crashing Strategy	Result Summary	Crash days
A	6	$1,000	Mode 1		
B	10	$1,000	Mode 1	**Duration = 30 days**	3
C	12	$1,000	Mode 1	**Total Cost = $9000**	3
D	8	$1,000	Mode 1		4
E	6	$1,000	Mode 1		3
F	4	$1,000	Mode 1		2

(b) Delayed schedule before compression



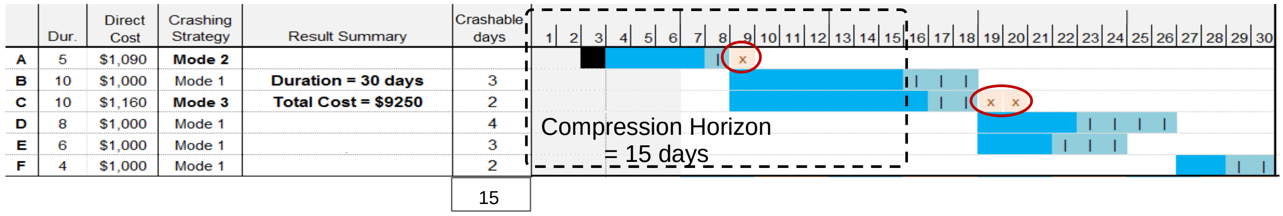
	Dur.	Direct Cost	Crashing Strategy	Result Summary	Crashable days
A	6	$1,000	Mode 1		2
B	10	$1,000	Mode 1	**Duration = 33 days**	3
C	12	$1,000	Mode 1	**Total Cost = $9300**	4
D	8	$1,000	Mode 1		4
E	6	$1,000	Mode 1		3
F	4	$1,000	Mode 1		2
					18

(c) Compression plan 1



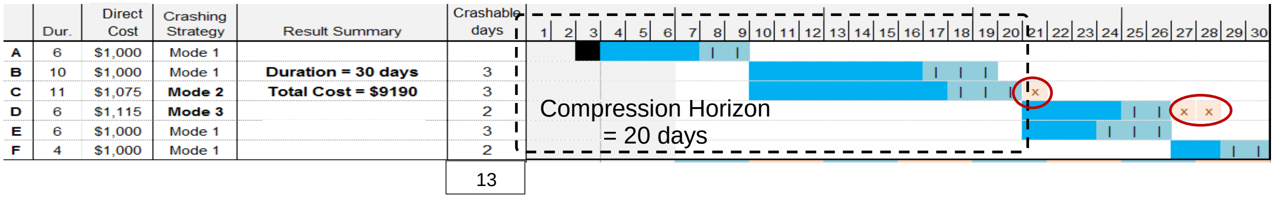
	Dur.	Direct Cost	Crashing Strategy	Result Summary	Crashable days
A	4	$1,210	**Mode 3**		
B	10	$1,000	Mode 1	**Duration = 30 days**	3
C	11	$1,075	**Mode 2**	**Total Cost = $9285**	3
D	8	$1,000	Mode 1		4
E	6	$1,000	Mode 1		3
F	4	$1,000	Mode 1		2
					15

(d) Compression plan 2



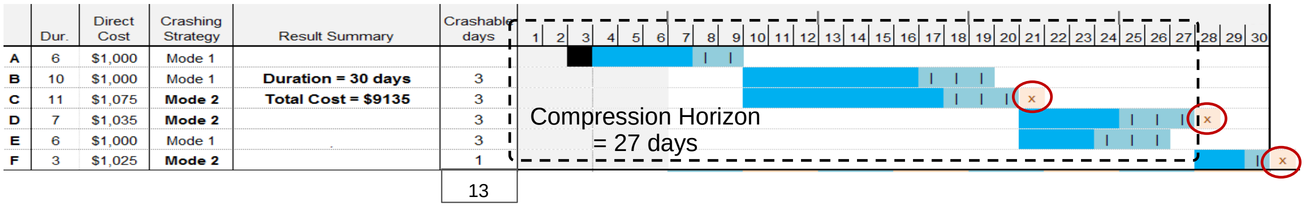
	Dur.	Direct Cost	Crashing Strategy	Result Summary	Crashable days
A	5	$1,090	**Mode 2**		
B	10	$1,000	Mode 1	**Duration = 30 days**	3
C	10	$1,160	**Mode 3**	**Total Cost = $9250**	2
D	8	$1,000	Mode 1		4
E	6	$1,000	Mode 1		3
F	4	$1,000	Mode 1		2
					15

(e) Compression plan 3



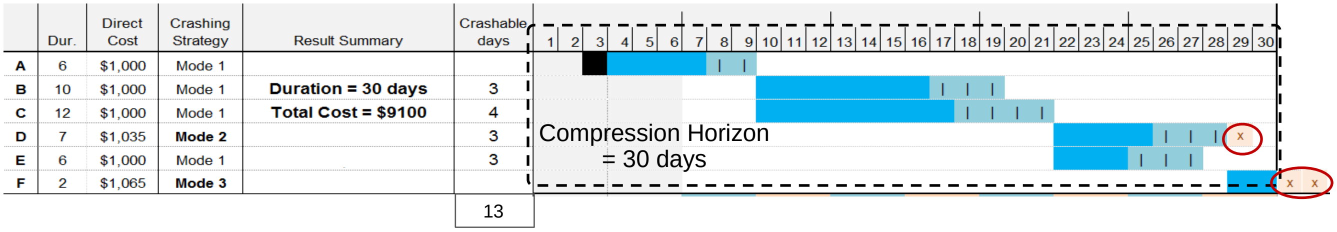
	Dur.	Direct Cost	Crashing Strategy	Result Summary	Crashable days
A	6	$1,000	Mode 1		
B	10	$1,000	Mode 1	**Duration = 30 days**	3
C	11	$1,075	**Mode 2**	**Total Cost = $9190**	3
D	6	$1,115	**Mode 3**		2
E	6	$1,000	Mode 1		3
F	4	$1,000	Mode 1		2
					13

(f) Compression plan 4



	Dur.	Direct Cost	Crashing Strategy	Result Summary	Crashable days
A	6	$1,000	Mode 1		
B	10	$1,000	Mode 1	**Duration = 30 days**	3
C	11	$1,075	**Mode 2**	**Total Cost = $9135**	3
D	7	$1,035	**Mode 2**		3
E	6	$1,000	Mode 1		3
F	3	$1,025	**Mode 2**		1
					13

(g) Compression plan 5 (Traditional TCT)



	Dur.	Direct Cost	Crashing Strategy	Result Summary	Crashable days
A	6	$1,000	Mode 1		
B	10	$1,000	Mode 1	**Duration = 30 days**	3
C	12	$1,000	Mode 1	**Total Cost = $9100**	4
D	7	$1,035	**Mode 2**		3
E	6	$1,000	Mode 1		3
F	2	$1,065	**Mode 3**		
					13

Figure 4: Corrective action plans with different compression horizons

Table 1: Alternative compression plans that meet a 30-day deadline

Experiment	Dur.	Crash Cost ($)	Total Cost ($)	Residual Crash Days	Exhausted Flexibility (days)*	
					Short-term	Long-term
Baseline (no compression)	30	$0	$9,000	18		
Delayed Schedule	33		$9,300	18		
Possible Corrective actions with varying compression horizons:						
Plan1: horizon = 10 days	30	$285	$9,285	15	A(2) & C(1)	
Plan2: horizon = 15 days	30	$250	$9,250	14	A(1) & C(2)	
Plan3: horizon = 20 days	30	$190	$9,190	13		C(1) & D(2)
Plan4: horizon = 27 days	30	$135	$9,135	13		C(1), D(1)& F(1)
Plan5: horizon = 30 days	30	$100	$9,100	13		D(1) & F(2)

* Circled days in Figure 4.

From the results in Table 1 and Figure 4, some observations can be made as follows:

- The delayed schedule before compression (Figure 4a), has 18-days crashable days and full Schedule Flexibility;
- The 5 compression plans recover the 3-day delay by crashing different combinations of activities, resulting in different crashing costs and Schedule Flexibilities;
- In general, crashing early activities (A and C) represents a plan to speed the recovery (e.g., Plan 1 and Plan 2), which showed to be costly, but retains higher residual crashable days because it does not affect the later activities that have higher preferences to stay intact in order to handle project future delays;
- Crashing middle activities (C and D) represents a slower recovery plan (e.g., Plan 3), which showed to be less costly, but exhibits less residual crashable days and less Schedule Flexibility;
- Crashing later activities (D and F) represents a delayed recovery plan (e.g., Plan 4 and Plan 5), which showed to be least costly but exhibits least residual crashable days and the least Schedule Flexibility;
- From the results above, there is a direct relationship between cost and recovery speed and schedule flexibility. This cost-flexibility trade-off have to be considered to choose among alternative corrective-action plans;
- Plan 5 (Figure 4g), is a minimum total-cost plan ($9,100), which is the typical plan produced by traditional time-cost trade-off analysis. This plan is the cheapest, where the last activity in the project is crashed because of its cheap cost of crashing. This plan, however, overlooks the impact on long-term flexibility of the schedule, and thus comes at the expense of much rigidity in the schedule. Accepting this plan at the early stage of the project rapidly consumes flexibility and this represents a high project risk, not only due to the lack of future crashing options, but also may prove costly as subsequent crashing will have to deal with only expensive options;
- Plan 1 (Figure 4c), is a maximum flexibility and fastest recovery plan. It crashes early activities, thus maximizing the Schedule Flexibility. Despite of the high cost, it is one of the good corrective actions to use in time-cost-flexibility optimization. If cost is an issue, then Plan 2 also represents a good time-cost-flexibility trade-off plan. Although they show higher total cost at this cycle of

corrective action, they still have high reserve capacity to reduce cost at the next cycle, which is a better approach for reducing project risk; and

- From the above, it is advisable to always monitor the cost-flexibility relationship at each reporting period before deciding a schedule compression plan. It can be wise to pay a little premium to increase flexibility at the beginning of the project, then later as construction becomes systematic and well managed, to resort to least cost plan at later cycles of corrective actions.

Overall, the results above prove that residual schedule flexibility and compression horizon are important dimensions that are essential to extend typical time-cost analysis, and lead to efficient ways to compress projects in a cost-effective and less risky manner.

5 DISCUSSION AND FUTURE IMPROVEMENTS

In the project management domain, flexibility is a term that can be associated with other terms such as resilience, which refers to the ability of a system to return to original (or better) situation after experiencing a disturbance. Mitchell and Harris (2012) defined resilience as “the ability of a system and its components to anticipate, absorb, accommodate, or recover from the effects of a shock or stress in a timely and efficient manner”. Resilience has been applied to different disciplines, for example, ecosystem stability (Gunderson 2009), engineering infrastructure (Tierney and Bruneau 2007), psychology (Lee et al. 2009), and behavioral sciences (Norris et al. 2008). It is possible, therefore, that the schedule flexibility concept introduced in this paper can be extended in future work to embody a quantitative representation of project resilience as a component of project control in construction.

The schedule flexibility concept of this paper is useful to both the owner and the contractor. If a contractor, particularly at early stages of construction, submits a schedule that involves all critical activities that have no options, the project becomes very risky to all parties. Quantifying and discussing schedule flexibility, therefore, encourages better communication among parties; soliciting optional construction methods; and optimizing decisions. It also adds to the practicality and constructability of construction schedules.

Many areas of improvements are still needed to address the current limitations, including:

- Ongoing efforts (almost completed) target to introduce an index to embody the schedule flexibility and used to compare between different schedule plans;

- Enhance flexibility formulation with a representation of possible activity overlapping, which is an important approach to compress projects, considering flexible activity; and

- Perform optimization experiments to determine the minimum compression horizon that maximizes flexibility, then minimize cost within this horizon. In this case, both flexibility, recovery speed, and cost are optimized.

6 CONCLUDING REMARKS

This research is a step towards optimum corrective action planning. The paper proposed a Schedule Flexibility concept that can readily be used to measure the residual flexibility of any proposed corrective-action plan. A simple case study was used to demonstrate the proposed computation and experiment of Schedule Flexibility with different compression plans. The case study proved that a fast recovery plan actions can be costly, but has the advantage of a large residual compressibility. Slowing the recovery plan, however, can be less costly but can quickly absorb the schedule flexibility. The paper thus argues that time, cost, compression horizon and flexibility are four important metrics that can identify the optimum compression plan. The optimum trade-off among them can decrease the risk of not meeting project constraints and gives the schedule better ability to absorb further execution challenges.

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