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OPTIMIZED ACCELERATION IN LINEAR SCHEDULING

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Abstract:

This paper introduces a novel algorithm for optimized acceleration of repetitive projects considering crew work continuity. The model enables planners of this class of projects to identify the optimal/near optimal relaxation time of each activity that leads to minimized project duration and interruption time. The model computations are organized in three modules:(1) a scheduling module designed to generate early and late start schedules, which are utilized to identify the prioritized activities for relaxation; (2) an activity-relaxation total float module that considers the total number of days that the early finish date of each activity (i) in each unit (j) can be relaxed without delaying the early start of its successor activities and without impacting the project duration; (3) an intermediate scheduling module that relaxes each activity in all of its repetitive sections based on its defined activity-relaxation total float to generate a near optimal schedule that simultaneously minimize project duration and work interruptions. An application example of a repetitive construction project is analyzed to demonstrate the capabilities of the developed model in generating a near optimal schedule that account for targeted objectives of project duration and interruptions' time.

Keywords: Acceleration, Repetitive project, linear scheduling, Crew work continuity.

1. Introduction:

Schedule acceleration of repetitive construction projects is a complicated task mainly due to the constraint of crew work continuity in this class of project (Moselhi et al. 2016). Accelerating the wrong activity will lead to spending more money without any effect on a project's duration, or spending more money than needed (Bakry et al. 2014). A variety of scheduling models are proposed in the literature for accelerating project schedule. These can be divided into five categories (1) heuristic procedures (Siemens 1971; Hazini et al. 2013); (2) mathematical programming (Henderickson and Au 1989; Pagnoni 1990); (3) simulation (Wan 1994); (4) integration of simulation with genetic algorithms (Feng et al. 2000; Ding et al. 2010; Zheng et al. 2004; Hazini et al. 2014); and (5) genetic algorithms and fuzzy set theory (Eshtehardian et al. 2008a, 2008b). However, these techniques are all addressing traditional (non-repetitive) projects and are unusable for repetitive projects. In spite of the unique constraints associated with repetitive construction projects such as precedence relationship, crew availability, and crew work continuity, there are fewer efforts concerning accelerating repetitive construction project. Only three algorithms have been proposed for accelerating this class of projects; all utilize relative alignment of successive activities to identify activities to accelerate in repetitive projects (Hassanein and Moselhi 2005; Bakry et al. 2014; Moselhi et al. 2016).

Although the literature provides more practical solutions for accelerating repetitive projects, none of the proposed methods account for prioritizing activities for relaxation. Additionally, their usage is limited only for a strict application of the work continuity constraint for all construction crews.

Unlike the existing tools and techniques cited above, the developed model provides a novel algorithm which is capable to identify the prioritized activities for relaxation enabling for crew work interruptions. The proposed model is capable of simultaneously minimizing project duration and crew work interruptions by identifying the optimum crew formation for the identified prioritized activities for relaxation at unit execution level.

2. Proposed Model:

The main benefit of the proposed model relies on identifying and quantifying the prioritized activities for relaxation in repetitive projects. However, most of scheduling models introduced in the literature for repetitive construction did not consider the impact of delaying the early finish dates of repetitive activities on minimizing project duration and crew work interruptions.

The proposed model highlights how relaxation of repetitive activities within their newly introduced activity-relaxation total float leads to minimizing project duration and crew work interruptions. The proposed model consists of three modules as follows:

2.1 First Module: Scheduling Module

The main objective of this module is to identify the feasible boundaries of each activity (i) in each unit (j) in order to prioritize activities for relaxation as shown in Figure 1. To do so, an automatic algorithm which is divided into four different phases was developed. The following sections of the paper describe the development of the four phases.

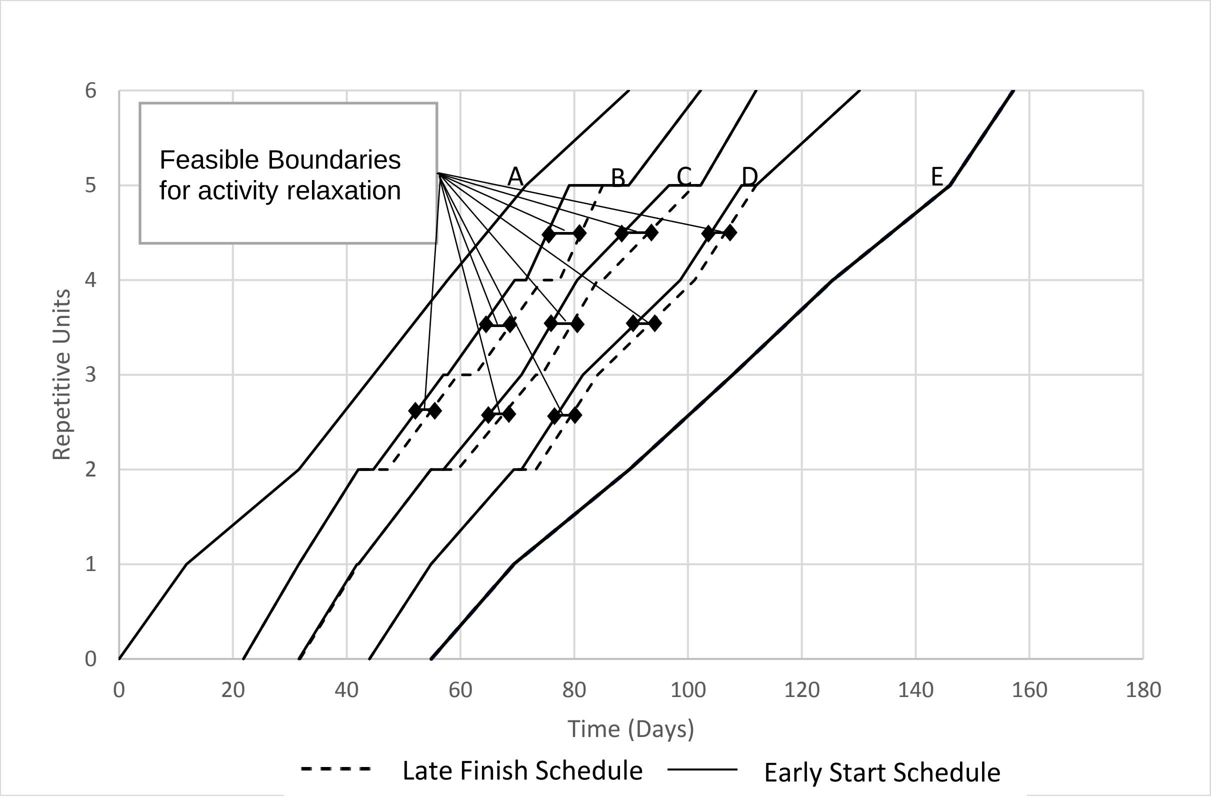


Figure 1: Feasible boundaries for activity relaxation (an example of a repetitive construction project).

2.1.1 Phase 1: Creates an initial project schedule

In the first phase of the developed algorithm, an initial project schedule was formulated as shown in the left side of Figure 2. The initial project schedule provides the shortest possible duration for the project while complying with the job logic/precedence relationships and crew availability constraints.

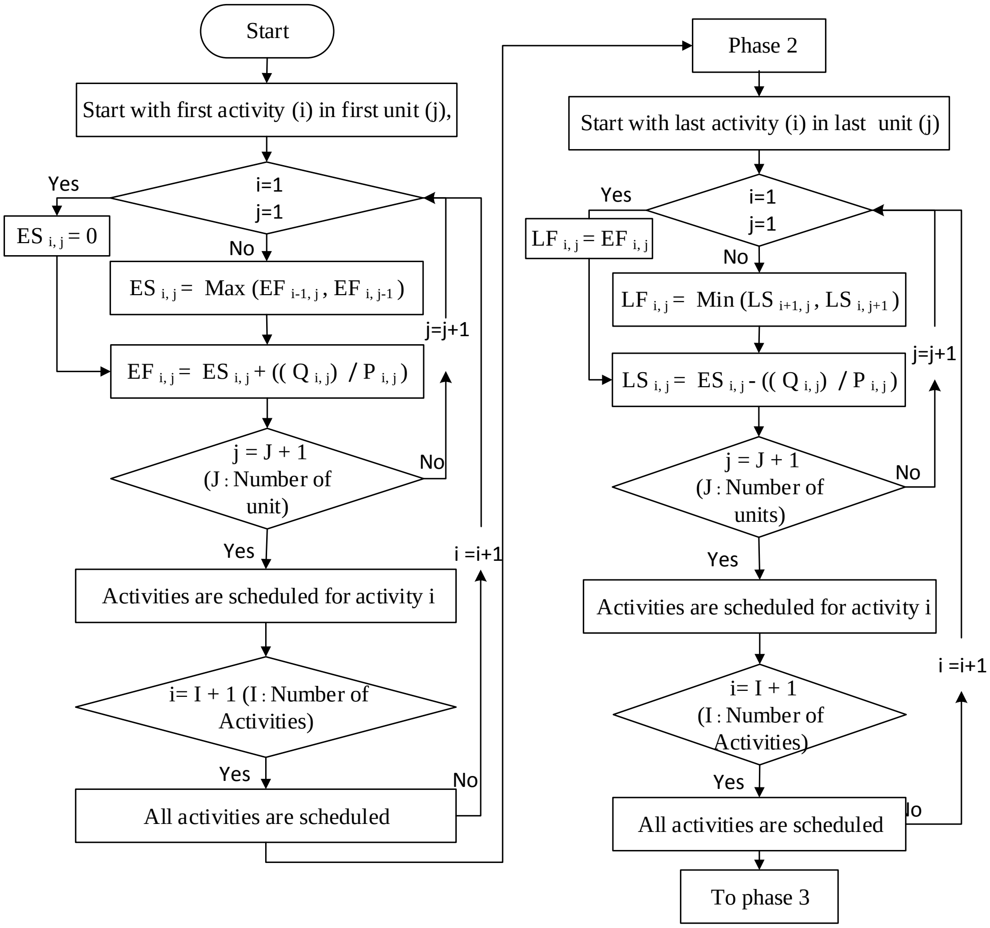


Figure 2: Flowchart of phases 1 and 2 of the developed algorithm.

2.1.2 Phase 2: Calculate late start schedule

In the second phase of the developed algorithm, the late start schedule was calculated. The objective of this phase is to start activities as late as possible to reduce work interruptions between activities without delaying the project. This is achieved by identifying the late start and finish dates of construction for each activity (i) at each repetitive unit (j), as shown in the right side of Figure 2.

where:
LFi,j: Late finish date of activity (i) at repetitive unit (j).
EFi,j: Early finish date of activity (i) at repetitive unit (j).
LFi,j: Late finish date of activity (i) at repetitive unit (j).
$LS_{i+1,j}$: Late start date of successor activity (i +1) at repetitive unit (j).
$LS_{i,j+1}$: Late start date of activity (i) at next repetitive unit (j +1).
LSi,j: Late start date of activity (i) at repetitive unit (j).
Qi,j: quantity of activity (i) at repetitive unit (j).
Pi,j: Productivity rate of activity (i) at repetitive unit (j).

2.1.3 Phase 3: Calculate early start schedule

This phase of the developed algorithm is designed to revise the late start schedule generated in phase 2 by starting the activities as soon as possible as shown in Figure 3. The feasible boundary for activity relaxation in unit (j) of activity (i) was identified by comparison between the schedule developed in this phase and the one in phase two of the developed algorithm. The crew work interruptions of activity (i) between unit (j) and (j-1) is calculated as shown in Eq.1. The total interruption duration of the project is formulated as depicted in Eq. 2.

[1] $\text{Inter}^{i}_{j,j-1} = ES_{i,j} - EF_{i,j-1}$

[2] $\text{TID} = \sum_{i=1}^{I} \sum_{j=1}^{J} ES_{i,j} - Ef_{i,j-1}$

where:
$\text{Inter}_{i,j\,,j-1}$: Interruption of activity (i) at repetitive unit (j) and (j-1).
ESi,j: Early start date of activity (i) at repetitive unit (j).
EFi,j-1: Early finish date of activity (i) at previous repetitive unit (j-1).
TID: Total interruption duration of project
ESi,1: Early start date of activity (i) at first repetitive unit (1).
EFi,j: Early finish date of activity (i) at repetitive unit (j).

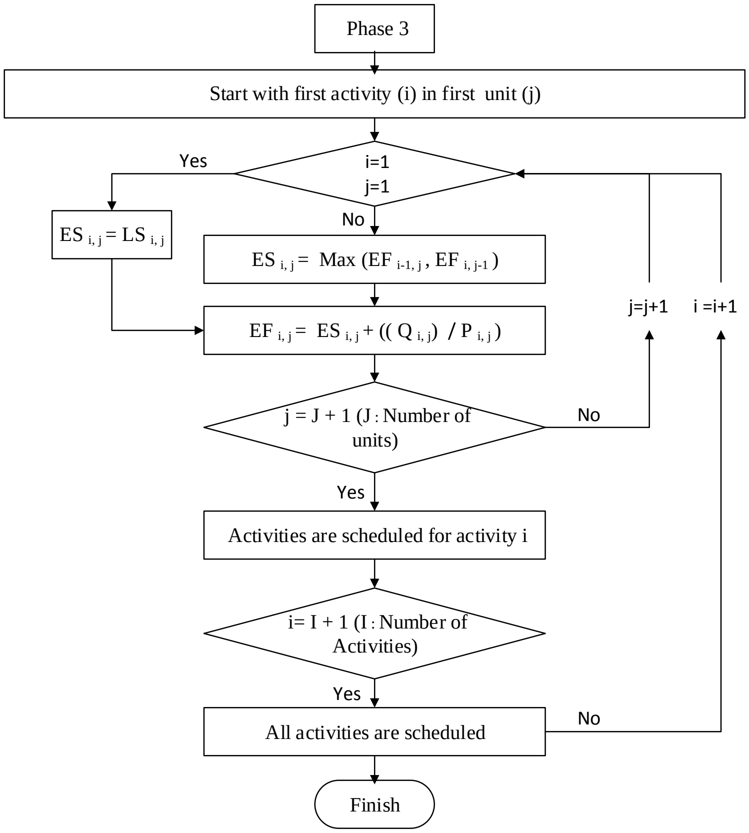


Figure 3: Flowchart of phase 3 of the developed algorithm.

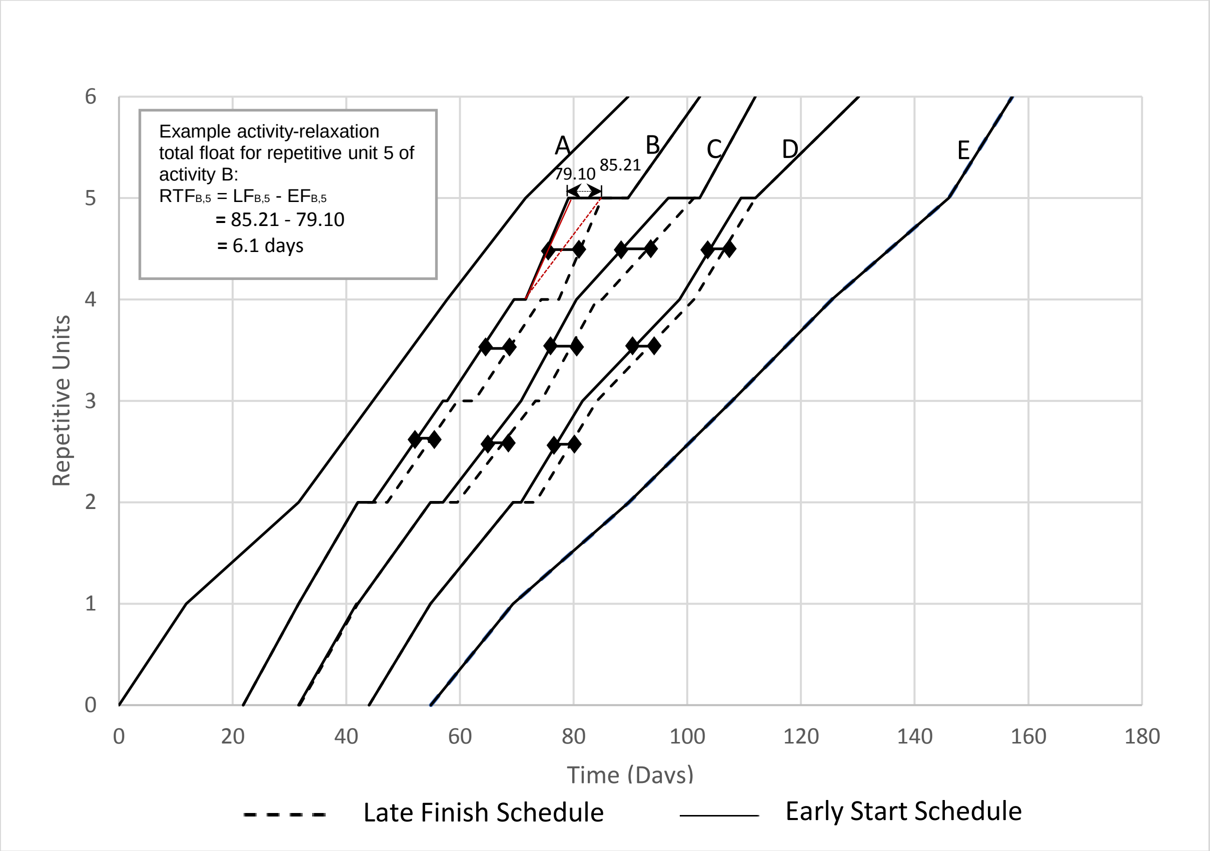
2.2 Second Module: Activity-Relaxation Total Float Module

In this study, a new type of activity-relaxation total float was introduced. It was defined as the maximum amount of time that the early finish date of a repetitive unit can be delayed, without either delaying its early start date or increasing project duration (D) and total crew work interruptions (TID). The activity-relaxation total float was calculated following the Eq 4.

[3] $RTF_{i,j} = LF_{i,j} - EF_{i,j}$

where:
RTFi,j: Activity–Relaxation Total Float of activity (i) at repetitive unit (j).
LFi,j: Late finish date of activity (i) at repetitive unit (j).
EFi,j: Early finish date of activity (i) at repetitive unit (j).

Accordingly, shifting the early finish date of a repetitive section within its activity-relaxation total float range would result in a set of intermediate schedules that maintain the minimum project duration and minimize total crew work interruptions. For example, by considering the availability of multiple crew formations, the early finish date of the fifth repetitive section of activity B can be delayed by up to 6.1 days without increasing the project duration as shown in Figure 4. In other words, the fifth repetitive section of activity B can be relaxed within its activity-relaxation total float range. By doing so, needed duration shortening can be achieved through assigning less additional accelerating resources.



Example activity-relaxation total float for repetitive unit 5 of activity B:
$RTF_{B,5} = LF_{B,5} - EF_{B,5}$
$= 85.21 - 79.10$
$= 6.1$ days

Figure 4: Activity-Relaxation Total Float example.

2.3 Third Module: Intermediate schedule module

The main objective of this module is to generate an optimum intermediate acceleration schedule for repetitive construction that simultaneously minimize project duration and crew work interruptions. The generated schedule module was used in this module to search for the total number of days that an activity can be relaxed in all of its repetitive sections based on its defined activity-relaxation total float without delaying the early start of its successor activities and without impacting the project duration. The computational process of this module is shown in Figure 5.

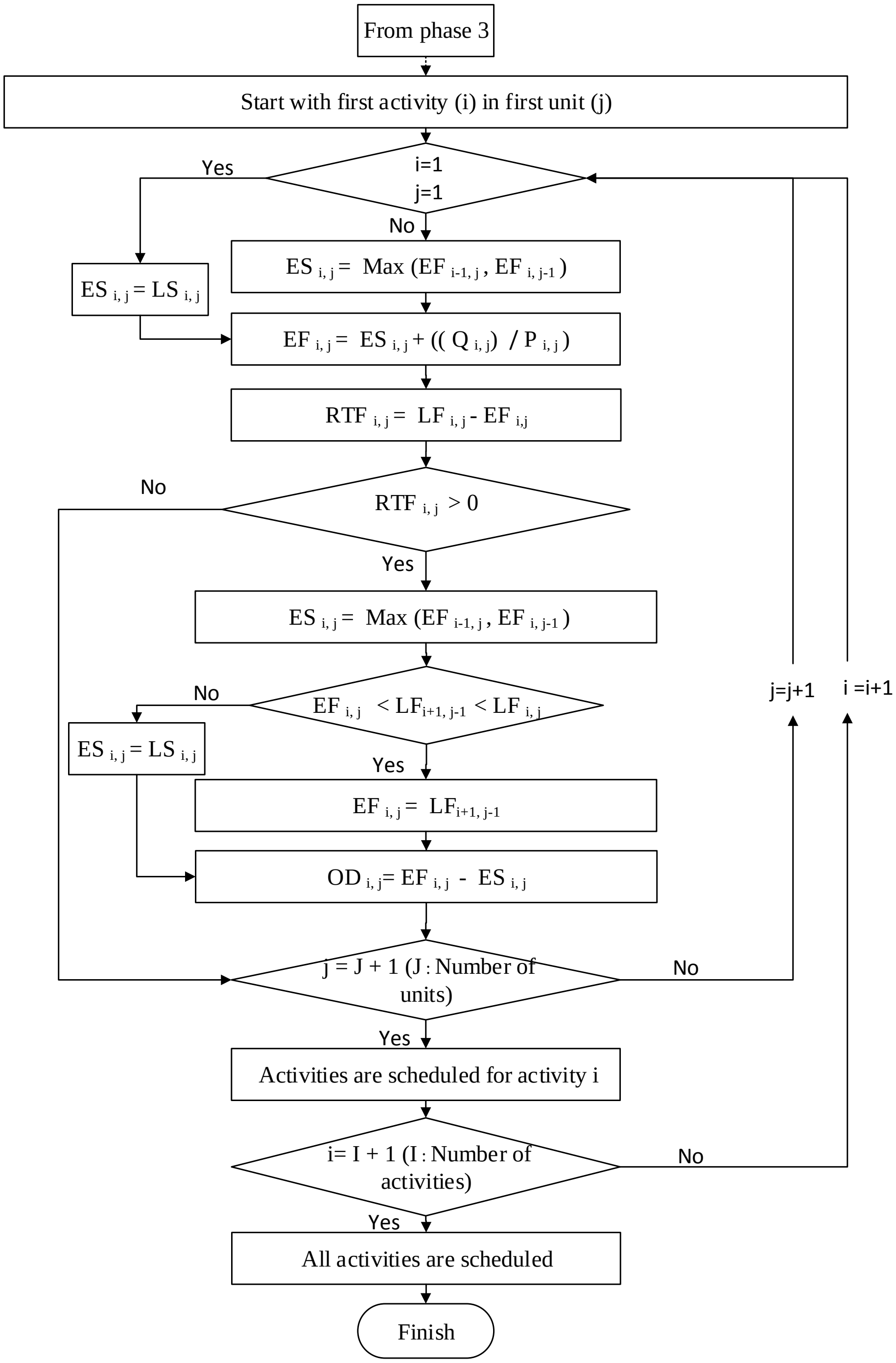


Figure 5: Algorithm for minimizing interruption durations utilizing Activity – Relaxation Total Float.

3. Application Example

For validation of the proposed model, an application example of a repetitive construction project was adapted from the literature. This case example was analyzed by several scholars (Russell and Caselton 1988; El-Rayes and Moselhi 2001; Nassar 2005; Liu and Wang 2007; Long and Ohsato 2009, and Altuwaim, A., & El-Rayes, K. 2018). The project includes five repetitive activates in sequence: excavations (Activity A), foundation (Activity B), columns (Activity C), beams (Activity D), and slabs (Activity E). Each of the aforementioned activities consists six similar units. The relationships among activities are specified to be finish to start with no lag time. The results of (Altuwaim, A., & El-Rayes, K. (2018)) were used for comparison due to allowing for crew work interruptions for the application example. Table 1 summarizes the required input data for the analyzed example that includes information of quantity (Qij) for each repetitive section (j) in each activity (i) and productivity rate (P_i).

Table 1: Required input data for application example

Repetitive activity (i)	Repetitive unit (j)	Q_{ij} (m^3)	P_i (m^3/day)
Activity A	1	1,090	92
	2	1,816	
	3	1,204	
	4	1,204	
	5	1,266	
	6	1,681	
Activity B	1	917	94.2
	2	983	
	3	1,163	
	4	1,109	
	5	714	
	6	1,186	
Activity C	1	88	8.6
	2	110	
	3	118	
	4	84	
	5	139	
	6	84	
Activity D	1	107	9.9
	2	144	
	3	107	
	4	169	
	5	107	
	6	180	
Activity E	1	126	8.7
	2	177	
	3	158	
	4	153	
	5	179	
	6	97	

The initial schedule as well as early and late stat schedule were calculated using the computation procedures in Figures 2 and 3 as shown in Table 2. The boundaries for activity relaxation were identified by calculating the activity-relaxation free float associated with each unit of each repetitive activity as shown in column 10 of Table 2. As such, activity relaxation is considered only for those activities which have a RTF more than zero. Furthermore, these computations identified the minimum duration of the project to be 157.2 days, as shown in Table 2.

Table 2: Schedule module computations for application example

Repetitive activity (i)	Repetitive unit (j)	Durations (days)	Initial schedule		Late start schedule		Early start schedule		RTF
			ES	EF	ES	EF	ES	EF	
Activity A	1	11.85	0	11.85	0	11.85	0	11.85	0
	2	19.74	11.85	31.59	11.85	31.59	11.85	31.59	0
	3	13.09	31.59	44.67	31.59	44.67	31.59	44.67	0
	4	13.09	44.67	57.76	44.67	57.76	44.67	57.76	0
	5	13.76	57.76	71.52	57.76	71.52	57.76	71.52	0
	6	18.27	71.52	89.79	71.52	89.79	71.52	89.79	0
Activity B	1	9.73	11.85	21.58	21.85	31.59	21.85	31.59	0
	2	10.44	31.59	42.02	31.59	42.02	31.59	42.02	0
	3	12.35	44.67	57.02	47.43	59.78	44.67	57.02	2.76
	4	11.77	57.76	69.53	62.76	74.54	57.76	69.53	5.00
	5	7.58	71.52	79.10	77.63	85.21	71.52	79.10	6.11
	6	12.62	89.79	102.42	89.79	102.42	89.79	102.42	0
Activity C	1	10.23	21.58	31.38	31.79	42.02	31.79	42.02	0
	2	12.79	42.02	54.81	42.02	54.81	42.02	54.81	0
	3	13.72	57.02	70.74	59.78	73.50	57.02	70.74	2.76
	4	9.77	70.74	80.51	74.54	84.30	70.74	80.51	3.80
	5	16.16	80.51	96.67	85.21	101.37	80.51	96.67	4.70
	6	9.77	102.42	112.18	102.42	112.18	102.42	112.18	0
Activity D	1	10.81	31.81	42.62	44.00	54.81	44.00	54.81	0
	2	14.55	54.81	69.36	54.81	69.36	54.81	69.36	0
	3	10.81	70.74	81.55	73.50	84.30	70.74	81.55	2.76
	4	17.07	81.55	98.62	84.30	101.37	81.55	98.62	2.76
	5	10.81	98.62	109.43	101.37	112.18	98.62	109.43	2.76
	6	18.18	112.18	130.36	112.18	130.36	112.18	130.36	0
Activity E	1	14.48	42.62	57.11	54.88	69.36	54.88	69.36	0
	2	20.34	69.36	89.70	69.36	89.70	69.36	89.70	0
	3	18.16	89.70	107.76	89.70	107.86	89.70	107.86	0
	4	17.59	107.86	125.45	107.86	125.45	107.86	125.45	0
	5	20.57	125.45	146.03	125.45	146.03	125.45	146.03	0
	6	11.15	146.03	157.17	146.03	157.17	146.03	**157.17**	0

The intermediate schedule was generated using the computation procedure in Figure 5 to generate a near optimal schedule that simultaneously minimize project duration and crew work interruptions as shown in columns 3 and 4 of Table 3. The crew work interruptions based on the proposed model and the model developed by Altuwaim, A., & El-Rayes, K. (2018) were compared as shown in column 5 and 8 Table 3. As shown in Table 3, the developed model out performed those of Altuwaim, A., & El-Rayes, K. (2018) in minimizing crew work interruptions from 28.16 days in Altuwaim's case to 18.28 days. This minimization was achieved by assigning less acceleration resources to those prioritized activities for relaxation within their activity-relaxation total float.

Table 3: Comparison of optimum solutions

Repetitive activity (i)	Repetitive unit (j)	Intermediate schedule by proposed model		Crew work interruption	Intermediate schedule by Altuwaim et al.(2018)		Crew work interruption
		ES	EF		ES	EF	
Activity A	1	0	11.85	-	0	11.85	-

	2	11.85	31.59	0	11.85	31.59	0
	3	31.59	44.67	0	31.59	44.67	0
	4	44.67	57.76	0	44.67	57.76	0
	5	57.76	71.52	0	57.76	71.52	0
	6	71.52	89.79	0	71.52	89.79	0
Activity B	1	21.85	31.59	-	21.85	31.59	-
	2	31.59	42.02	0	31.59	42.02	0
	3	44.67	59.79	2.65	44.67	57.02	2.65
	4	59.79	73.51	0	57.76	69.53	0.74
	5	73.51	84.32	0	71.52	79.10	1.99
	6	89.79	102.42	5.48	89.79	102.42	10.69
Activity C	1	31.79	42.02	-	31.79	42.02	-
	2	42.02	54.81	0	42.02	54.81	0
	3	59.79	73.51	4.97	57.02	70.74	2.21
	4	73.51	84.32	0	70.74	80.51	0
	5	84.32	101.39	0	80.51	96.67	0
	6	102.42	112.18	1.03	102.42	112.18	5.74
Activity D	1	44.00	54.81	-	44.00	54.81	-
	2	54.81	69.36	0	54.81	69.36	0
	3	73.51	84.32	4.15	70.74	81.55	1.38
	4	84.32	101.39	0	81.55	98.62	0
	5	101.39	112.20	0	98.62	109.43	0
	6	112.20	130.36	0	112.18	130.36	2.76
Activity E	1	54.88	69.36	-	54.88	69.36	-
	2	69.36	89.70	0	69.36	89.70	0
	3	89.70	107.86	0	89.70	107.86	0
	4	107.86	125.45	0	107.86	125.45	0
	5	125.45	146.03	0	125.45	146.03	0
	6	146.03	**157.17**	0	146.03	**157.17**	0
Total work interruption days				**18.28**			**28.19**

4. Conclusion:

This research presents a new model for acceleration of repetitive construction projects considering crew work continuity constraint. The developed model introduces a new type of activity-relaxation total float, based on crew availability that considers the impact of delaying the early finish dates of repetitive activities on crew work interruptions. The proposed model generates an intermediated acceleration schedule that simultaneously minimize project duration and crew work interruptions. The presented model provides an easy to use acceleration tool for repetitive construction without using optimization techniques.

The overall intermediate acceleration schedule is expected to assist project manager to benefit from the learning curve effect, minimizing equipment idle time, reducing firing and hiring of labor and retaining skilled labor. Example application is described to highlight the essential features of the developed model. Future research can focus on expanding the present model to quantify the impact minimizing crew work interruptions on project cost.

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