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Original Article

Scheduling the work of multiple construction crews working concurrently in repetitive construction projects

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Abstract

In repetitive construction projects such as roads, pipelines and multi-story buildings, schedulers might need to utilize multiple crews to simultaneously construct sub-activities of a particular activity to shorten their duration. Synchronizing the work of these crews while complying to their work continuity constraint is a challenging task due to the variation of activities quantities of work in each unit and the productivity rates of available crew formations for each activity. This paper presents a novel scheduling approach for repetitive construction projects that enables the concurrent utilization of multiple crews while complying with: (1)crew availability; (2) precedence relationships; and (3) crew work continuity constraints. An application example from the literature has been analyzed to validate the current approach, demonstrate its use and illustrate its novel capabilities. Results of this analysis showed that the suggested methodology successfully saved 8% in project duration in comparison to the least project duration achieved in the literature.

I. INTRODUCTION

Repetitive construction projects such as roads, pipelines and multi-story buildings always necessitate construction crews to repeat their work in each repetitive unit in the project, moving from one unit to another[1,2]. Such movement of crews should be scheduled promptly, where no crew has to remain idle until its predecessor crew finish work in the same unit[3,4]. This exclusive scheduling prerequisitefor such projects are often cited as crew work continuity constraint[5,6]. Fulfilling this requirement provides efficient use of resources by exploiting the learning curve effect, avoiding idle time of crews and holding on expert labor[7]. In order to satisfy this constraint,progress rate of activitiesshould be balanced using the productivity rate of its utilized crews.This is achieved by dividing such projects into several adjacent units where each unit comprises the same set of activates, which enables the utilization of multiple crews concurrently in each activity[8]. The concurrent utilization of multiple crews can significantly influence activity delivery rate and consequently activity duration[9]. However, scheduling the simultaneous work of these crews while maintaining their crew work continuity constraint is a challenging task due to the variation of: (1) activities quantities of work in each unit; and (2) the production rates of available crews for each activity.

Several models were developed to consider the concurrent utilization of multiple crews to perform each activity. These models utilized Line of Balance technique (LOB) to maximize resource utilization by balancing the production rate of each activity[10]. For example, Arditi *et al.* (1986) examined the advantages of LOB such as clear presentation of successive relationships between activities and ease of altering resource production rates to produce efficient solutions. Arditi *et al.,* (2002) presented instructions to improve the practicality of LOB in construction projects such as enabling cost analysis, learning curve effect and increasing the rate of delivery of selected activities. Gouda *et al.* (2017a) presented optimization algorithm to assign multiple crews while maintaining their work continuity constraints. Ammar (2013) and Damci (2020) investigated the harmonization of repetitive activities using LOB technique. Despite the original contributions of these models, theyassume fixed delivery rate for each repetitive activity andexploitsequal crews to construct each repetitive activity so as to maintain the natural rhythm concept (Damci 2020; Gouda *et al.* 2017) see Fig. 1. This assumption doesn't conform with reality due to the variation of quantities of work required in each repetitive unit and/or crew production rate(Monghasemi and Abdallah 2021). To deal with this limitation, Linear Scheduling Method (LSM) has been developed to schedule both typical and atypical repetitive activities (García-Nieves 2019). This technique enables the consideration of variable delivery rate for each repetitive activity[21]. For example,Harmelink (1995)formulated a linear scheduling model that is combined with AutoCAD based package. This study focused on recognizing the controlling activity path and computerizing linear scheduling process.Harmelink and Rowings (1998) introduced linear scheduling algorithm for repetitive projects thatdetermined the controlling activity path. Despite the original contributions of these models, it didn'tallow the utilization of multiple crews concurrently in each repetitive activity[2].Therefore, there is a need to develop a scheduling technique that allows for harmonizing the concurrent work of multiple construction crews having same\different productivity rates in each activity while maintaining crew work continuity constraint and complying with precedence relationships between activities. To overcome this challenge, this paper presents a novel scheduling technique for repetitive construction projects that enables the utilization of multiple concurrent crews in each repetitive activity.

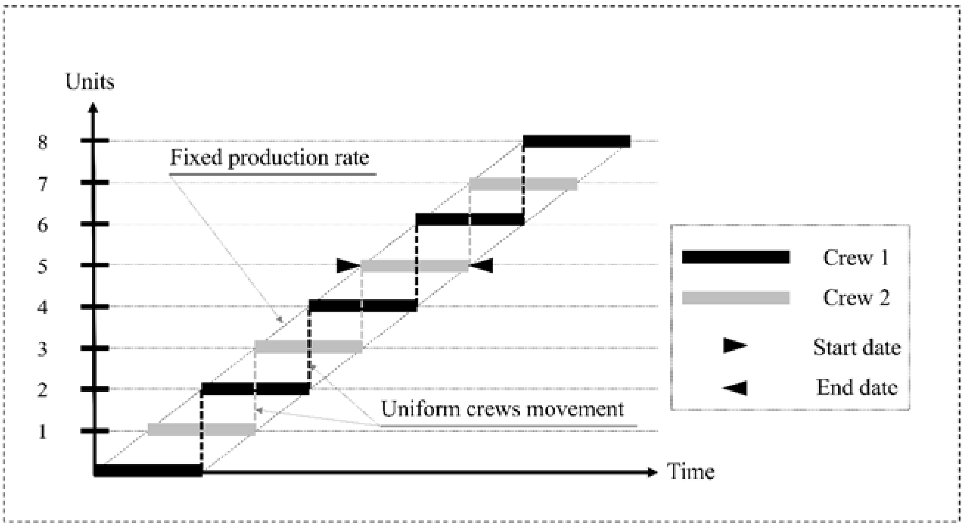

Fig. 1: Natural rhythm approach.

2. OBJECTIVE

The objective of this paper is to develop a novel scheduling technique for repetitive construction projectsto provide a practical resource-oriented schedules for repetitive construction projects that are capable of: (1) utilizing multiple crews to construct each repetitive activity concurrently with flexibility in their work sequence; (2) complying with crew work continuity constraints and precedence relationships among project activities; and (3) considering typical and atypical activities that have equal and variable quantities of work in each repetitive unit see Fig. 2. Detailed description of the proposed technique is presented in the subsequent section.

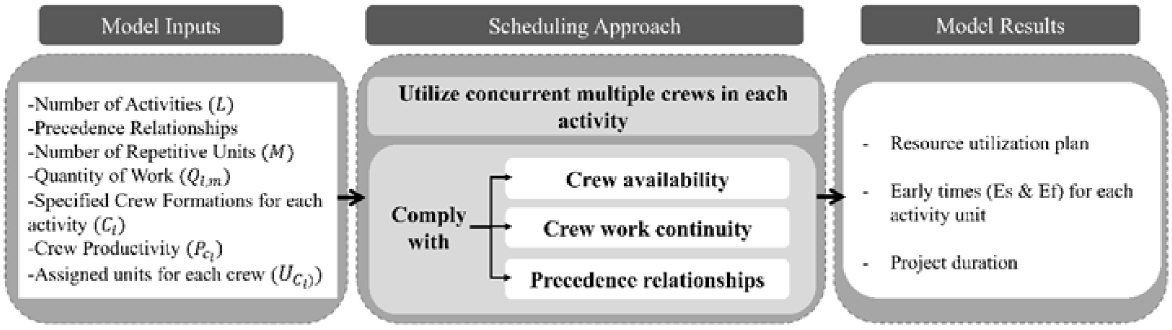

Fig. 2: Scheduling approach.

3. SCHEDULING TECHNIQUE

This technique is designed to provide the early timesfor each activity unit (*l,m*) based on the number of crews(C_l) that assigned to construct each activity(l) and their work sequence. The scheduling technique computations areperformed in the following steps:

1- The planner should specify the number of crews (*Cl*) that assigned to perform each activity(*l*) and their work sequence from the first unit (u = 1) to the last one(U) that is performed by each crew. For example, the planner has specified three excavation crews(C_E=3) to perform the excavation activity during the construction of a 12-house project(M = 12). Crew 1 can be assigned to five houses ($U_{1,E}$)=5) in the project (e.g., houses 1, 2, 6, 10, 11); crew 2 can be assigned to three other houses($U_{2,E}$)=3) in the project (e.g., houses 3, 5, 8); and crew 3 can be assigned to the remaining four houses($U_{3,E}$)=4) in the project (e.g., houses 4, 7, 9, 12). Therefore, the planner has flexibility to schedule large repetitive construction projects that necessitates the use of multiple crews by assigning same/different number of units without any restriction on the work sequence for each crew.

2- Calculate the duration ($d_{l,u}$) of each activity unit (*l,u*) based on its quantity of work ($Q_{l,u}$) and the production rate (P_{cl}) of its user-specified crew ($c_{l,u}$), as shown in Eq. 1.

$$d_{l,u} = \frac{Q_{l,u}}{P_{c_l}} \qquad \forall\ l \in L\&\ 1 \le u\ \ge\ U \quad (1)$$

Where,
$d_{l,u}$ is the duration of each activity unit (*l,u*).
$Q_{l,u)}$is the quantity of work of activity ($_l$) in unit ($_u$).
P_{cl} is the production rate of crew (*cl*) that is utilized to perform activity (*l*).

3- Calculate the primary early start ($PS_{l,u}$) and early finish ($PF_{l,u}$) forall activity units starting with first unit (*u* =) to the last one (U) that specified to each crew (*cl* =1 C_l) in each activity (*l*) while satisfying crew availability and precedence relationships, as shown in Eq. 2,3, 4, and 5. This calculation is based on the duration of each activity unit calculated in the previous step.

$$PS_{l,u} = 0 \qquad \forall\ l = 1\ \&u = 1 \quad (2)$$

$$PS_{l,u} = PF_{l-1,u} \qquad \forall\ 1 < l \le L\ \ \&u = 1 \quad (3)$$

$$PS_{l,u} = \max\left(PF_{l,u-1}\ , PF_{l-1,u}\right) \qquad \forall\ 1 < l \le L\ \ \&u > 1 \quad (4)$$

$$PF_{l.u} - PS_{l.u} + d_{l.u} \qquad \forall\ l \in L\&u \ge 1 \quad (5)$$

Where,
$PS_{l,u}$ is the primary early start of activity (l) in unit (u).
$PF_{l,u}$ is the primary early finish of activity (l) in unit (u).

4- Identify the total idle time for each crew (I_{Cl})among its specified units using Eq. 6 that resulted from considering activities precedence relationships in step 3.

$$I_{Cl} = \sum_{1}^{U}\left(PS_{l,u} - PF_{l,u-1}\right) \qquad \forall c_l \in C_l \quad (6)$$

Where,
I_{Cl} is the total idle time for each crew (*c*) in activity (*l*).

5- Calculate the early start ($S_{l,u}$) and early finish ($F_{l,u}$) for all activity units that comply with crew work continuity while maintaining crew availability and precedence relationships by shifting the primary timeswith the total idle time for the specified crew as shown in Eq. 7,8, and 9.

$$S_{l,u} = PS_{l,u} + I_{Cl} \qquad \forall\ l \in L\&u = 1 \quad (7)$$

$$S_{l,u} = PF_{l,u-1} \qquad \forall\ l \in L\&u > 1 \quad (8)$$

$$F_{l,u} = S_{l,u} + d_{l,u} \qquad \forall\ l \in L\&u \in U \quad (9)$$

Where,
$S_{l,u}$ is the early start of activity (l) in unit (u).
$F_{l,u}$ is the early finish of activity (l) in unit (u).

6- Steps 3 through 5 are repeated for all assigned crews form the first crew (cl) to the last crew (Cl) for each activity.

4. APPLICATION EXAMPLE

A three-span concreate bridge example[24–27] is analyzed using the current model to demonstrate the model capabilities and highlight the superiorities of its results over those of similar models in the literature. This example includes five activities that are repeated in four units, work quantities and the corresponding available crew formations data are listed in Table 1. The project activities are serial with all finish to start activities logical relationships. It is required to schedule the work of multiple crews working concurrently in each activity while maintaining their work continuity. In order to demonstrate the model use and to highlight its superiority, two different resource utilization scenarios are considered. In the first scenario, only one crew has been utilizedto perform each activity from the first unit to the last one, as shown in Table 2.

Table 1: Quantities of work in each activity unit and available crew data[27].

		Repetitive activities				
		Excavation	Foundation	Columns	Beams	Slabs
Quantities of work in each Repetitive unit in m^3	Unit 1	1147	1032	104	85	0
	Unit 2	1434	1077	86	92	138
	Unit 3	994	943	129	101	114
	Unit 4	1529	898	100	80	145
Productivity rates of available crew formations in m^3/ day	Crew 1	91.75	89.77	5.73	9.9	8.73
	Crew 2	-	71.81	6.88	8.49	7.76
	Crew 3	-	53.86	8.03	7.07	-
	Crew 4	-	-	-	5.66	-

Table 2: Solution of the first scenario (validation solution).

Sol.	Repetitive activities																				Duration (days)
	Excavation				Foundation				Columns				Beams				Slabs				
	Repetitive units																				
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	
	Utilized crews																				
Validation	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	142.9

This scenario resulted in the same early times for project activities and project duration as provided byHyari *et al.* (2009) model. In the second scenario, variable number of crews utilized to perform project activities. One crew utilized to perform the excavation activity, two different crews concurrently utilized to perform the foundation activity, one crew to perform the column activity, three crews to perform the beams activity and one crew to perform the slabs activity, as shown in Table 3. Scheduling calculations in this scenario have been carried out using the aforementioned equations (Eq. 1 through Eq. 9) as shown in Table 3. For more clarification, consider the foundation activity in the solution of the second scenario. The model utilized the aforementioned equations (Eq. 1 through Eq. 9) in the following steps:

1- Two different crews (crew one and crew two) have been assigned to perform this activity. The first crew performed the first three units and the second crew permed the last unit.

2- Use Eq. 1 to calculate the duration ($d_{l,u}$) of the foundation activity in each unit based on the quantity of work ($Q_{l,u}$) and the productivity rate (P_{cl}) of the utilized crew (cl).

3- Use Eq. 2 to Eq. 5 to calculate the primary early start and early finsh of the each activity in each unit in the project to comply with precedence relationships and crew availability. It should be mentioned here that this step results in having some crews to remain idel in ordet to comply with precedence relationships (waiting for the predecessor activity to be finished in the unit under consideration) as shown in Fig. 3.

4- Once the primary schedule is calculated, calculate the total idle time of each crew using Eq. 6 by adding up all the idle times per unit for the crew under consideration as shown in Table 3 (column 8 and 9).

5- Calculate the final schedule of each unit in this activity to comply with crew work continuity constraint by adjusting the primary schedule using Eq. 7, 8, and 9.

This scenario provided the early times for each activity unit while considering activities precedence relationships and crew work continuity constraints as shown in Table 3.

Table 3: Scheduling calculations for the second scenario.

Column no.	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Activity	Unit	Quantity of work	Utilized crew	Crew production rate	Activity. Duration ($d_{l,m}$)	($PS_{l,m}$)	($PF_{l,m}$)	Crew Idle time($I_{c,l}$)		($S_{l,m}$)	($F_{l,m}$)
(l)	(m)	(Ql,m)	(c)	(P_{cl})	Eq. 1	Eq. 2 to 5.		Per unit	Eq. 6	Eq. 7 to 9.	
Excavation	1	1147	1	91.75	12.50	0.0	12.5	0.0	0.0	0.0	12.5
	2	1434	1	91.75	15.63	12.5	28.1	0.0		12.5	28.1
	3	994	1	91.75	10.83	28.1	39.0	0.0		28.1	39.0
	4	1529	1	91.75	16.66	39.0	55.6	0.0		39.0	55.6
Foundation	1	1032	1	89.77	11.50	12.5	24.0	0.0	4.1	16.6	28.1
	2	1077	1	89.77	12.00	28.1	40.1	4.1		28.1	40.1
	3	943	1	89.77	10.50	40.1	50.6	0.0		40.1	50.6
	4	898	2	71.81	12.51	55.6	68.1	0.0	0.0	55.6	68.1
Columns	1	104	3	8.03	12.95	24.0	36.9	0.0	4.4	28.4	41.4
	2	86	3	8.03	10.71	40.1	50.8	3.2		41.4	52.1
	3	129	3	8.03	16.06	50.8	66.9	0.0		52.1	68.1
	4	100	3	8.03	12.45	68.1	80.6	1.2		68.1	80.6
Beams	1	85	2	8.49	10.01	36.9	47.0	0.0	3.9	40.8	50.8
	2	92	2	8.49	10.84	50.8	61.7	3.9		50.8	61.7
	3	101	1	9.9	10.20	66.9	77.1	0.0	0.0	66.9	77.1
	4	80	3	7.07	11.32	80.6	91.9	0.0	0.0	80.6	91.9
Slabs	1	0	-	-	-	-	-	-	-	-	-
	2	138	1	8.73	15.81	61.7	77.5	0.0	1.4	63.0	78.8
	3	114	1	8.73	13.06	77.5	90.5	0.0		78.8	91.9
	4	145	1	8.73	16.61	91.9	108.5	1.4		91.9	108.5

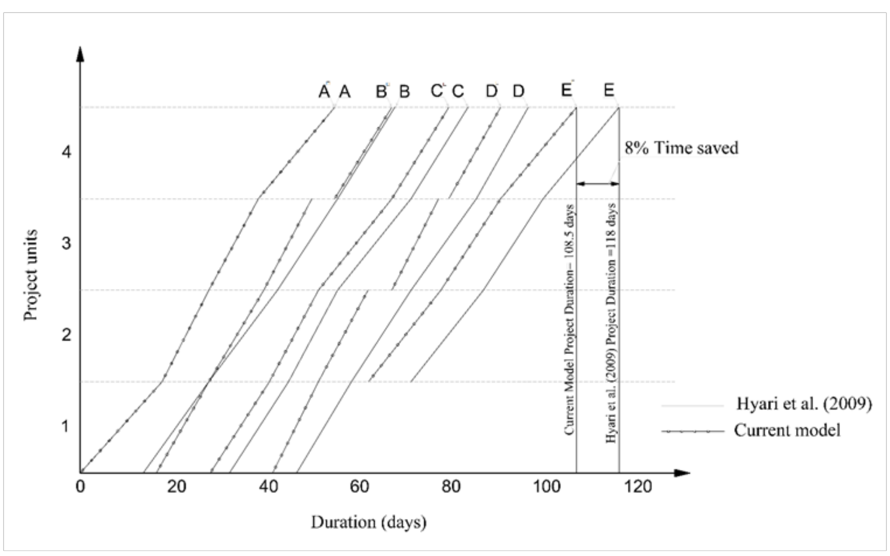

Fig. 3: Comparison between the solution of the current model and Hyari *et al.*(2009) model.

In addition to that, this solution resulted in project duration of 108.5 days, which saves 8% in project duration in comparison to the best solution provided by model (118 days) as shown in Fig. 3 and Table 4. This superiority was achieved because of the original capabilities of the model to schedule smooth continuous movement of multiple concurrent crews working in each activity without the need for any of these crews to remain idle. This provides schedulers with more flexibility to produce practical schedules with minimum durations.

Table 4: Solution comparison with Hyari *et al.* (2009) model in the second scenario

	Repetitive activities																			
	Excavation				Foundation				Columns				Beams				Slabs			
Sol.	Repetitive units																			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
	Utilized crews																			
Hyari *et al.* (2009) model	1	1	1	1	2	2	2	2	1	1	1	1	3	3	3	3	3	3	3	3
Current model	1	1	1	1	3	1	2	2	3	3	3	3	2	1	1	1	1	1	1	1

5. Conclusion

A novel scheduling approach was developed and presented for repetitive construction projects to enable the utilization of multiple crews in each activity concurrently and comply with crew work continuity constraint. Computations of the current approach are formulated based on two major criterions. First, calculate the primary schedule that comply with crew availability and precedence relationships. Second, calculate the final early times schedule by shifting the primary schedule with the total idle time for each crew to comply with crew work continuity while maintaining crew availability and precedence relationships. The current approach was utilized to analyze an application example to demonstrate its capabilities and superiority over previous models. Results of this analysis showed that the present approach successfully provided 8% saving in project duration in comparison to the least project duration achieved.The main achievement of this research is its original methodology to enable producing practical resource-oriented schedules for repetitive construction projects that are capable of: (1) utilizing multiple concurrent crews having same/variable productivity rates to construct each repetitive activity with flexibility in their work sequence; (2) maintaining crew work continuity constraints and precedence relationships among project activities; and (3) scheduling typical and non-typical activities that have equal and variable quantities of work in each repetitive unit.

6. Appendix

$d_{l,u}$= the duration of each activity unit (l,u).
$Q_{l,u}$ = the quantity of work of activity (l) in unit (u).
Pcl = the production rate of crew (cl) that is utilized to perform activity (l).
$PS_{l,u}$= the primary early start of activity (l) in unit (u).
$PF_{l,u}$ = the primary early finish of activity (l) in unit (u).
I_{Cl} is the total idle time for each crew (c) in activity (l).
$S_{l,u}$ is the early start of activity (l) in unit (u).
$F_{l,u}$ is the early finish of activity (l) in unit (u).

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