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Minimum Cost Method for Multiskilled Resource Scheduling

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Abstract:

Conventional multiskilled resource scheduling is restricted to immediate resource replacement regardless of whether a resource is worth replacing financially. Furthermore, information is lacking on the extent to which an activity can be expedited or delayed under resource constraints. This study presents an algorithm for multiskilled resource scheduling that aims to enhance the decision process, yield results, and eliminate waste related to resource replacement. The first step addresses the initial solution selected from the lowest scheduling cost among forward-pass and backward-pass calculations. The second step identifies the resource-constrained float, in which an activity can be shifted forward or backward with a guarantee of an adequate resource combination and of meeting the project deadline. The final step uses the given float, which allows for flexibility in adjusting the project schedule to optimise resource replacement. The proposed algorithm is simple and can be calculated manually. It provides a solution that is superior to that of the optimisation approach in the optimal resource replacement step. Furthermore, its advantages can be practically applied in large projects that demand a large number of activities and resources. The results of real-world project case study reveal that the proposed algorithm minimises total project cost.

Keywords: multiskilled resource scheduling; resource replacement; resource-constrained float; total project cost

1. INTRODUCTION

Construction projects involve activities that require the use of resources to achieve certain goals. The fundamental resources necessary for such projects include people, money, methods, materials, and machines. However, these resources are limited because there is usually more than one activity that demands the same resources. As a result, resource shortages become unavoidable and cause project delays and increased project costs.

Single-skilled resource scheduling based on two calculation approaches has been researched over several decades [1, 2, 3, 4, 5, 6, 7]. One approach is the traditional forward-pass calculation, which attempts to start an activity as early as possible. The other approach is the backward-pass calculation, which aims to start an activity as late as possible. It is possible to determine the float of the activity after the completion of both calculations even with limited resources. However, the effect of the result on reducing project cost remains unclear. As long as activities are scheduled within their float, the project cost will remain unchanged owing to identical resource usage (Figure 1).

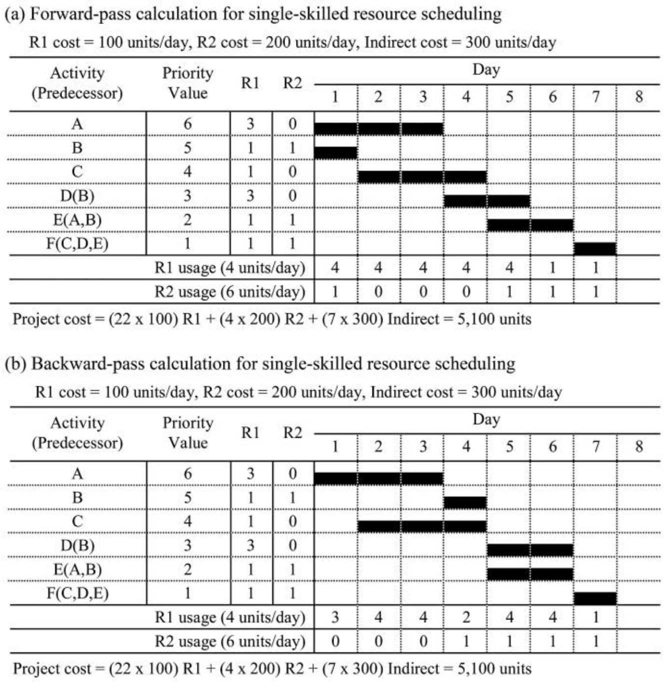

Figure 1. Calculation approaches of single-skilled resource scheduling

The proposed approach assumes that a resource has multiple skills and can be used to generate efficient resource utilisation for project scheduling. This assumption is based on the fact that workers possess various skills and can adjust themselves to any of them. The results of several studies on this topic demonstrate that the multiskilled ability of a worker contributes to productivity, quality, and continuity. Furthermore, it contributes to greater flexibility in work assignment among construction project managers [8, 9, 10]. Related studies also discovered that a multiskilled resource approach benefits workers regarding longer employment duration, better work qualification, and higher job satisfaction [11, 12, 13].

Existing multiskilled resource scheduling relies solely on a forward-pass calculation [14, 15, 16]; forward- and backward-pass calculations may result in different project costs because of different resource combinations. Furthermore, a forward-pass calculation may not guarantee a lower project cost than a backward-pass calculation (Figure 2). Therefore, it is necessary to perform both calculations to obtain an improved solution. Figure 2 also demonstrates an alternative solution in which the start time of activities is adjusted within the float obtained from calculations. Accordingly, the reduction of resource replacement minimises the total project cost.

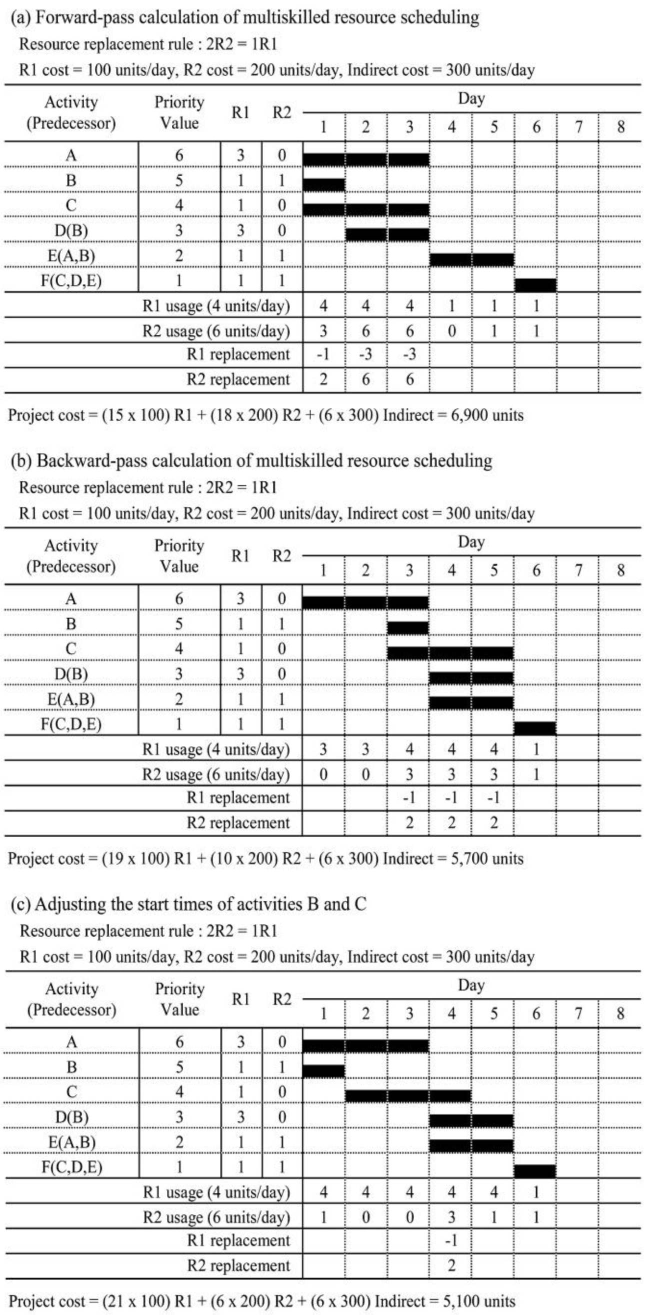

Figure 2. Project cost from different approaches of multiskilled resource scheduling

In summary, existing multiskilled resource scheduling still has limitations in determining the float of an activity under resource constraints. Furthermore, there is no information regarding the adjustment of the start time of an activity within its float to reduce project cost.

2. MINIMUM COST METHOD (MCM ALGORITHM)

MCM algorithm is developed to improve the results of multiskilled resource scheduling. This algorithm attempts to determine the lowest project cost. A resource-constrained float is the period in which an activity can move forward or backward while guaranteeing an adequate resource combination and meeting the project deadline. The given float allows for flexibility in adjusting the project schedule to minimise resource replacement and reduce the total project cost. MCM algorithm consists of three main steps (Figure 3):

(1) determination of the initial solution,
(2) determination of the resource-constrained float, and
(3) determination of the optimal resource replacement.

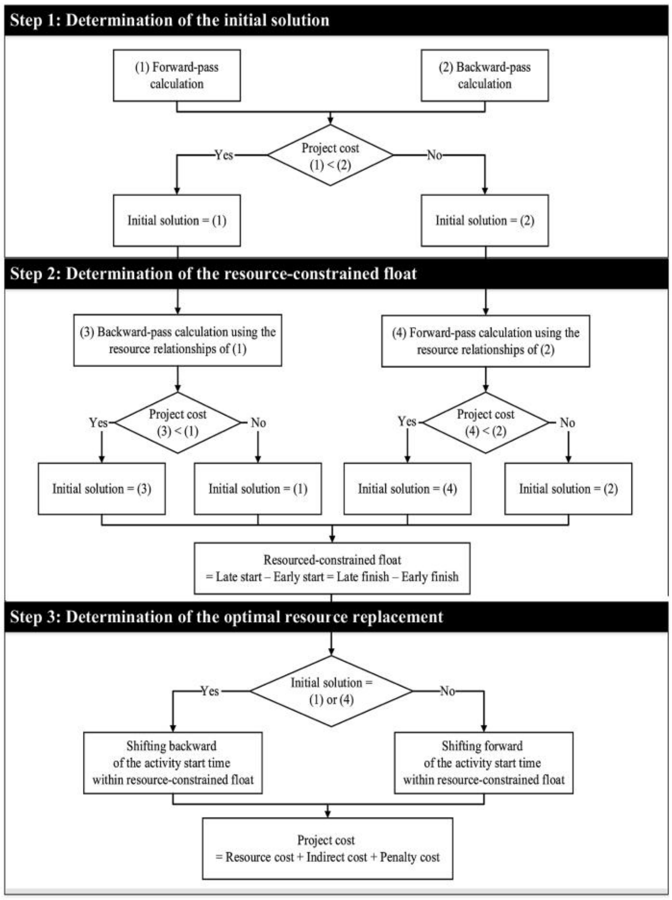

Figure 3. MCM algorithm steps

2.1 Step 1: determination of the initial solution

In a forward-pass calculation, the eligible activities are required to be activities with completed predecessors and selected for resource allocation. The resource allocation of a forward-pass calculation focuses on activity priority in descending order. Therefore, resources are first allocated to

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the activity with higher priority. There are several criteria for determining the priority of activities; however, in this example, a late start time calculated by the critical path method (Figure 4) is used as a means of identifying activity priority. The activity with the earliest late start time is considered the most important activity. If certain activities do not have sufficient resources, the remaining qualified resources from the resource pool and the lower priority activities will replace them. However, if the qualified resources are insufficient, the activities will be delayed (Figure 5).

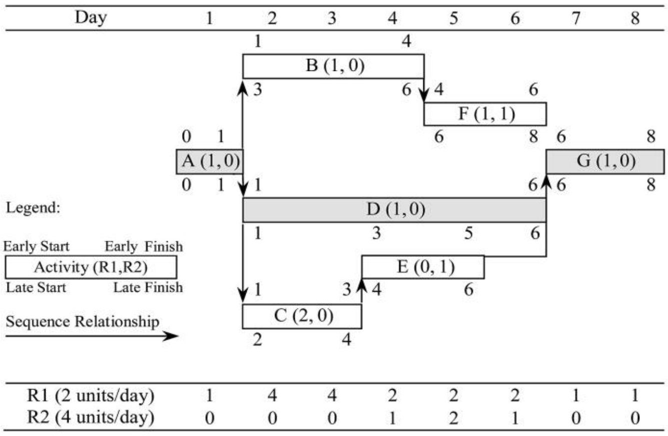

Figure 4. CPM network

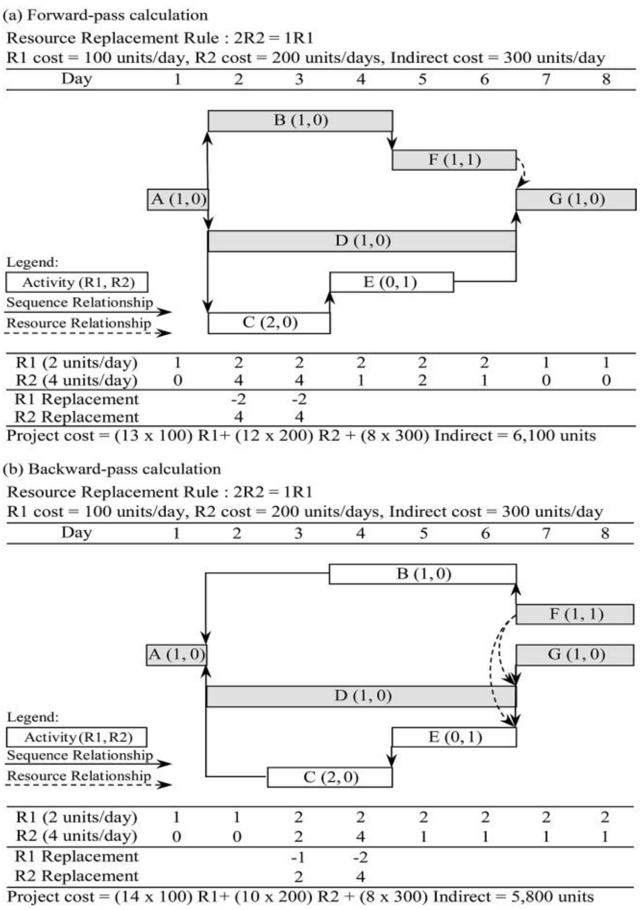

Figure 5. The 1st step of MCM algorithm

Figure 5 shows that activity A, which has no predecessor but has sufficient resources, can be started on day 1. On day 2, resources are allocated to activities B, C, and D because of the completion of the predecessor (activity A). The resources are then allocated to activities D, C, and B. On days 2 and 3, although activities C and B lack two R1 resources (1R1 for activity C and 1R1 for activity B), they can proceed with the work because four R2 resources can replace them (2R2 = 1R1 for activity C and 2R2 = 1R1 for activity B). On day 4, all activities have sufficient resources; therefore, activity E can be started on this day. Activity E can also be started on day 4 because its predecessor (activity C) is completed on day 3. Following the completion of activity B (day 4), activities E and F can be started on day 5. After activities D and F are completed on day 6, their resources are released to start activity G on day 7. Activities F and G have a resource relationship even though there is no sequence relationship between them. The project completion time is on day 9, and the project cost is 6,100 units. Owing to the additional resource relationship, the path consisting of activities A, B, F, and G, which is referred to as the critical path of this project, is created.

Multiskilled resource scheduling is not only a forward-pass calculation but also a backward-pass calculation. A backward-pass calculation allows each activity to start as late as possible with limited resources. A backward-pass calculation is performed from the project completion time (obtained from a forward-pass calculation) to the project start time. The eligible activities are required to be activities that can be completed no later than the start times of their successors. The resource allocation of a backward-pass calculation focuses on activity priority in ascending order. Therefore, resources are initially allocated to lower priority activities. If certain activities have insufficient resources, the remaining qualified resources from the resource pool and the activities with higher priority will replace them. However, if the qualified resources are insufficient, the activities are expedited (Figure 5).

Figure 5 shows that activities F and G, which have no successors but have sufficient resources, can be completed by the project deadline, which is derived from forward-pass calculation (day 8). Therefore, they can be started on day 7. Thereafter, their resources are released to activity B (predecessor of activity F) and activities D and E (predecessors of activity G). Although there is no sequence relationship between activities D, E, and F, there is a resource relationship between them. During days 5 and 6, sufficient resources are allocated to activities E, B, and D in that order. On days 3 and 4, although activity C lacks one and two R1 resources, it can proceed because two and four R2 resources can be used as replacements, respectively. Given that activity A can be started on day 1, the project completion time is guaranteed to be on day 8. This results in a project cost of 5,800 units, which is lower than that produced by forward-pass calculation. Owing to the additional resource relationship between activities D and F, the path consisting of activities A, D, and F, which is known as the critical path of this project, is created.

The aforementioned examples demonstrate that different resource relationships can produce different critical paths, thus leading to different project costs because of different combinations of resources. Furthermore, forward-pass scheduling may not guarantee a lower project cost than backward-pass scheduling. Therefore, it is necessary to use the lower project cost as the criterion for the initial solution. In summary, backward-pass scheduling is selected as the initial solution for the second step.

2.2 Step 2: determination of the resource-constrained float

This step aims to determine the float under limited resources for each activity in the initial solution. The initial solution must perform a reverse calculation by retaining the same resource relationship to guarantee that the critical paths remain the same. As a result, the mistake of obtaining the previous expensive scheduling can be avoided. Thus, forward-pass calculation is performed again by using the same resource relationship as that in the initial solution (backward-pass calculation) (Figure 6).

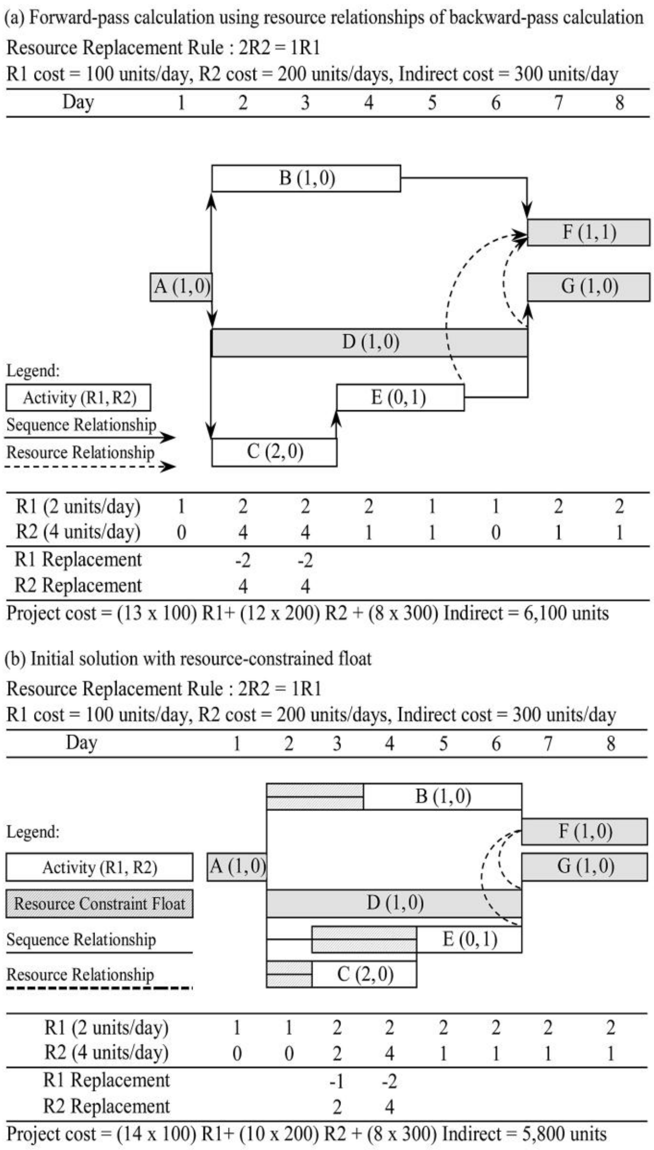

Figure 6. The 2nd step of MCM algorithm

In Figure 6, the solution of the forward-pass calculation appears to be the same as the previous calculation (Figure 5). However, the difference is the start time of activity F. The resource relationship between activities D and F causes activity F to be started after the completion time of activity D. As a result, the path consisting of activities A, D, and F remains the same critical path as that in the initial solution (backward-pass scheduling). Owing to the higher project cost of a forward-pass calculation, backward-pass scheduling is retained as the initial solution.

When the forward- and backward-pass calculations are completed, they can determine the resource-constrained float of each activity. The resource-constrained float can be calculated by the following relationship in (1):

$$F_r = LS_r - ES_r = LF_r - EF_r. \quad (1)$$

where F_r is the resource-constrained float, ES_r is the early start time under resource constraints, EF_r is the early completion time under resource constraints, LS_r is the late start time under resource constraints, and LF_r is the late completion time under resource constraints.

By using the relationship in (1), noncritical activities B, C, and D in the initial solution can be identified (Figure 6).

2.3 Step 3: determination of the optimal resource replacement

This step continues the efforts of improving the lower project cost of the initial solution. It is possible to shift the start time of a noncritical activity to a point within its resource-constrained float to reduce resource replacement. A reduction in resource replacement leads to a lower project cost. Therefore, a heuristic algorithm based on a shifting sequence is required. The criteria for shifting a sequence forward for forward-pass scheduling focuses on early completion time under resource constraints. A noncritical activity with the latest early completion time under resource constraints is performed first (Figure 7). By contrast, the criteria for shifting back a sequence for backward-pass scheduling focuses on a late start time under resource constraints. Therefore, a noncritical activity with the earliest late start time under resource constraints is performed first (Figure 7).

Figure 7 also shows the improvement process using the aforementioned algorithm. Backward shifting leads to noncritical activities C, B, and E being performed in that order. First, activity C is shifted back to start on day 2. As a result, the replacement of resource R2 is reduced by two units. Accordingly, the project cost decreases to 5,500 units, thus reducing the initial solution by 300 units. Shifting activity B then results in a larger resource replacement; therefore, the start time of activity B should not be shifted by even one day. It should be noted that the results remain the same regardless of whether activity E is shifted. On the basis of this process, the project cost of the initial solution can be reduced to the minimum cost.

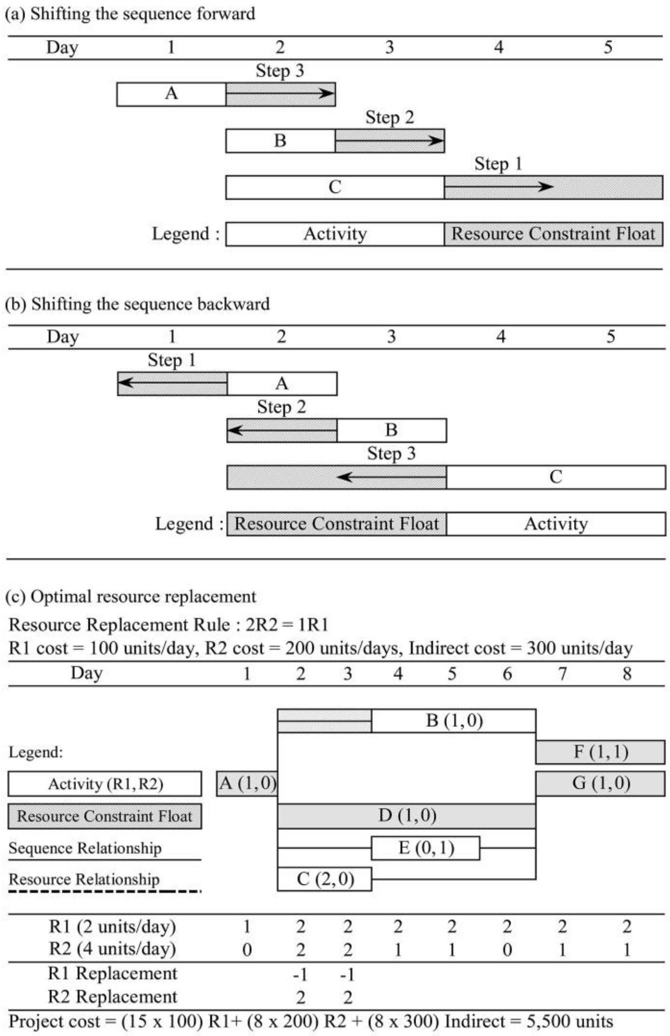

Figure 7. The 3rd step of MCM algorithm

3. REAL-WORLD PROJECT CASE STUDY

Table 1 shows a real-world project case study involving activities, resources, and project data. The project is calculated by the CPM network to be 200 days regardless of any resource limits. The MCM algorithm is applied to this real-world project case study to clarify the concept and verify the solution.

3.1 Step 1: initial solution

A heuristic approach for assigning, replacing, and releasing resources on the basis of an algorithm for multiskilled resource scheduling, namely, Augmented Heuristic Algorithm for Multi-skilled Resource Scheduling [14], was applied to the project case study. Two approaches for resource scheduling were calculated manually (Table 2 and Table 3).

Table 2 shows that the forward-pass calculation starts at the beginning of the project (day 1). The only eligible activities are site preparation and piling, which are sorted by activity priority on the basis of the shortest processing time rule, which states that a shorter activity duration leads to higher activity priority. Considering that these two activities are in order, if site preparation can start accordingly, three labors will be unavailable for piling. Thus, site preparation is started on day 1 and can be completed on day 10. Before delaying piling, the process verifies the remaining qualified resources for replacing insufficient labors for piling (4 carpenters = 2 labors and 2 steel workers = 1 labor). Accordingly, piling can be started on day 1 and completed on day 15.

On day 20, excavation is completed, and the eligible activities are underground utility (continued from the previous decision-making stage), formwork of footing and rebar of footing (successors of excavation) with the sequence relationship from excavation. After considering these activities sequentially, formwork of footing can be started only after replacing one insufficient carpenter with two qualified plasterers (2 plasterers = 1 carpenter). Furthermore, rebar of footing can be started only after replacing one insufficient labor with two qualified plasterers (2 plasterers = 1 labor) and replacing two insufficient steel workers with two plasterers and two painters (2 plasterers = 1 steel worker and 2 painters = 1 steel worker) in that order.

After underground utility is completed on day 22, formwork of footing and rebar of footing are completed on day 30, their resources are released to the resource pool and assigned to eligible activity at the next decision-making stage (day 31). Thereafter, the resources in the resources pool returned by underground utility, formwork of footing and rebar of footing are assigned to concrete of footing (a current eligible activity). As a result, this activity can be started on day 31. Therefore, underground utility, formwork of footing and rebar of footing have a resource relationship with concrete of footing. However, concrete of footing already has a sequence relationship with formwork of footing and rebar of footing; therefore, it is not necessary to create a resource relationship between them. This process is then continued until all activities are scheduled. Finally, forward-pass scheduling is completed with a project duration of 203 days and a project cost of 2,946,400 THB.

In Table 3, the backward-pass calculation starts at the end of the project (day 203, derived from forward-pass calculation). The only eligible activities are landscaping, fence and gate, interior painting, wooden floor, window, receptacles and switches, stud and lintel, ceiling work, plumbing fixtures, HVAC, concrete of stair and concrete of floor which are sorted by activity priority on the basis of a reverse shortest processing time rule, which states that a shorter activity duration leads to lower activity priority. Considering day 195, receptacles and switches is already completed and released their resources to the resource pool. Thereafter, these resources are assigned to window. As a result, there are four qualified plumbers and two qualified electricians that are available to replace two insufficient labors (4 plumbers = 2 labors) and one insufficient carpenters (2 electricians = 1 carpenter) for window, respectively. Therefore, receptacles and switched has a resource relationship with window. This process is continued up to the beginning of the project and results in a project duration of 203 days and a project cost of 2,918,950 THB.

When the forward- and backward-pass calculations are completed, the results of the first step are obtained (Table 4). It can be seen that the project cost obtained from a backward-pass calculation is lower. Thus, scheduling using a backward-pass calculation is selected as the initial solution.

Table 1. Real-world project case study

ID	Activity	Duration (day)	Predecessors	Daily resource requirement (persons)								
				Labor (LAB)	Carpenter (CAR)	Steel Worker (STW)	Plasterer (PLT)	Painter (PAT)	Welder (WEL)	Roofer (ROF)	Plumber (PLB)	Electrician (ELE)
1	Site Preparation	10		5	2	2	3	3	3		2	2
2	Piling	15		6		3	2					
3	Excavation	5	1,2	5	1							
4	Underground Utility	7	1,2	3	2	3	2		2		5	4
5	Formwork of Footing	10	3	3	5				3			
6	Rebar of Footing	10	3	3		6						
7	Concrete of Footing	7	5,6	5			5					
8	Formwork of Ground Column	9	7	2	4				3		1	1
9	Rebar of Ground Column	6	7	2		5						
10	Concrete of Ground Column	2	8,9	3			4					
11	Formwork of Ground Beam	15	7	3	5				3			
12	Rebar of Ground Beam	12	7	4		6						
13	Concrete of Ground Beam	2	11,12	4			5					
14	Termite Protection	2	13	5								
15	Backfill	10	4,10,14	5								
16	Formwork of Column	20	13,15	5	5				3			
17	Rebar of Column	15	13,15	5		6						
18	Concrete of Column	7	16,17	5			5					
19	Formwork of Beam	20	16	5	5				3			
20	Rebar of Beam	15	17	5		7						
21	Concrete of Beam	7	19,20	6			6					
22	PC Floor	5	21	5					1			
23	Formwork of Floor	3	21,22	5	5				3			
24	Rebar of Floor	2	21,22	4		6						
25	Concrete of Floor	1	23,24	5			6					
26	Formwork of Stair	10	21	2	3				2			
27	Rebar of Stair	7	21	2		6						
28	Concrete of Stair	2	26,27	2			3					
29	Roof Trusses	15	18	2					5			
30	Roof Sheathing	5	29	2						5		
31	Masonry Wall	25	21	3			6					
32	Ductwork	3	30	2					2		5	2
33	Electrical System	5	30	2								5
34	HVAC	2	32,33	2								6
35	Plumbing Fixtures	4	32,33	2							5	
36	Stud and Lintel	7	31	1	3	2	2					
37	Plastering Work	20	31	2			4					
38	Wall Ceramic Tile	15	31	2			3					
39	Floor Ceramic Tile	15	31	2			3					
40	Ceiling Work	5	38,39	1	2		2					
41	Door	7	38,39	2	3							
42	Window	8	38,39	2	2							
43	Drywall	15	37	1	2		3		2			
44	Wooden Floor	10	37	1	3							
45	Cabinet and Counters	8	41		3			1	1			
46	Interior Painting	10	43,45	2				5				
47	Exterior Painting	15	43,45	2				6				
48	Receptacles and Switches	7	43	1								3
49	Fence and Gate	10	47	4	2	1	5	2	2			1
50	Landscaping	12	47	5			4	2				
	Daily resource limit (persons/day)			8	6	7	8	8	5	5	5	6
	Daily resource cost (THB/day)			300	400	500	600	650	700	750	800	850
	Resource replacement rules: 2 persons of inexpert worker = 1 person of expert worker											
	Contract duration = 240 days											
	Indirect cost = 3,000 THB/day											
	Penalty cost = 5,000 units/ day											

Table 2. Forward-pass calculation

Time	ID	Activity	Priority Value	Resource LAB 8	CAR 6	STW 7	PLT 8	PAT 8	WEL 5	ROF 5	PL 5	EL 6	Duration	Decision	Forward Finish	Resource Replacement	Sequence Relationship	Resource Relationship
1	1	Site Preparation	10	5	2	2	3	3	3	0	2	2	10	Start	10			
	2	Piling	15	6(-3)+3	0+4	3+2	2	0	0	0	0	0	15	Start		4CAR=2LAB, 2STW=1LAB		
11	2	Piling		6	0	3	2	0	0	0	0	0	15	Continu	15			
16	3	Excavation	5	5	1	0	0	0	0	0	0	0	5	Start	20		1 2	
	4	Underground Utility	7	3	2	3	2	0	2	0	5	4	7	Start			1 2	
21	4	Underground Utility		3	2	3	2	0	2	0	5	4	7	Continu	22			
	5	Formwork of Footing	10	3	5(-1)+1	0	0+2	0	3	0	0	0	10	Start		2PLT=1CAR	3	
	6	Rebar of Footing	10	3(-1)+1	0	6(-2)+2	0+4	0+2	0	0	0	0	10	Start		2PLT=1LAB, 2PLT=1STW, 2PAT=1STW	3	
23	5	Formwork of Footing		3	5	0	0	0	3	0	0	0	10	Continu	30			
	6	Rebar of Footing		3	0	6	0	0	0	0	0	0	10	Continu	30			
31	7	Concrete of Footing	7	5	0	0	5	0	0	0	0	0	7	Start	37		5 6	4
38	9	Rebar of Ground Column	6	2	0	5	0	0	0	0	0	0	6	Start	43		7	
	8	Formwork of Ground	9	2	4	0	0	0	3	0	1	1	9	Start			7	
	12	Rebar of Ground Beam	12	4	0	6(-4)+4	0+8	0	0	0	0	0	12	Start		8PLT=4STW	7	
	11	Formwork of Ground	15	3(-3)+3	5(-3)+3	0	0	0+8	3(-1)+1	0+4	0+	0	15	Start		6PAT=3LAB, 2PAT=1CAR, 4ROF=2CAR,	7	
44	8	Formwork of Ground		2	4	0	0	0	3	0	1	1	9	Continu	46			
	12	Rebar of Ground Beam		4	0	6	0	0	0	0	0	0	12	Continu				
	11	Formwork of Ground		3(-1)+1	5(-3)+3	0	0+8	0+2	3(-1)+1	0	0	0	15	Continu		2PLT=1LAB, 6PLT=3CAR, 2PAT=1WEL		
47	12	Rebar of Ground Beam		4	0	6	0	0	0	0	0	0	12	Continu				
	11	Formwork of Ground		3	5	0	0	0	3	0	0	0	15	Continu				
	10	Concrete of Ground	2	3(-2)+2	0	0	4+4	0	0	0	0	0	2	Start	48	4PLT=2LAB	8 9	
49	12	Rebar of Ground Beam		4	0	6	0	0	0	0	0	0	12	Continu	49			
	11	Formwork of Ground		3	5	0	0	0	3	0	0	0	15	Continu				
50	11	Formwork of Ground		3	5	0	0	0	3	0	0	0	15	Continu	52			
…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…
177	48	Receptacles and Switches	7	1	0	0	0	0	0	0	0	2	7	Start	183		43	43 44 45
	46	Interior Painting	10	2	0	0	0	5	0	0	0	0	10	Start			43 45	42 44
	47	Exterior Painting	15	2+2	0+4	0	0	6(-3)+3	0	0	0	0	15	Start		2LAB=1PAT, 4CAR=2PAT	43 45	42 44
184	46	Interior Painting		2	0	0	0	5	0	0	0	0	10	Continu	186			
	47	Exterior Painting		2+4	0+2	0	0	6(-3)+3	0	0	0	0	15	Continu		4LAB=2PAT, 2CAR=1PAT		
187	47	Exterior Painting		2	0	0	0	6	0	0	0	0	15	Continu	191			
192	49	Fence and Gate	10	4	2	1	5	2	2	0	0	1	10	Start	201		47	46 48
	50	Landscaping	12	5(-1)+1	0+4	0	4(-1)+1	2	0	0	0	0	12	Start		2CAR=1LAB, 2CAR=1PLT	47	46 48
202	50	Landscaping		5	0	0	4	2	0	0	0	0	12	Continu	203			

Table 3. Backward-pass calculation

Time	ID	Activity	Priority Value	Resource									Duration	Decision	Backward Start	Resource Replacement	Sequence Relationship	Resource Relationship
				LAB	CAR	STW	PLT	PAT	WEL	ROF	PLB	ELE						
				8	6	7	8	8	5	5	5	6						
203	50	Landscaping	12	5	0	0	4	2	0	0	0	0	12	Finish				
	49	Fence and Gate	10	4(-1)+1	2	1+4	5(-1)+1	2	2	0	0	1	10	Finish		2STW=1LAB, 2STW=1PLT		
	46	Interior Painting	10	2(-2)+2	0	0	0	5(-1)+1	0+2	0+4	0	0	10	Finish		2WEL=1LAB, 2ROF=1LAB, 2ROF=1PAT		
	44	Wooden Floor	10	1(-1)+1	3	0+2	0	0	0	0	0	0	10	Finish		2STW=1LAB		
	42	Window	8	2(-2)+2	2(-1)+1	0	0	0	0	0	0+4	0+2	8	Finish	196	4PLB=2LAB, 2ELE=1CAR	38 39	48
	48	Receptacles and Switches	7	1(-1)	0	0	0	0	0	0	0	3	7	Delay				
	36	Stud and Lintel	7	1(-1)	3(-3)	2(-2)	2(-2)	0	0	0	0	0	7	Delay				
	40	Ceiling Work	5	1(-1)	2(-2)	0	2(-2)	0	0	0	0	0	5	Delay				
	35	Plumbing Fixtures	4	2(-2)	0	0	0	0	0	0	5(-4)	0	4	Delay				
	34	HVAC	2	2(-2)	0	0	0	0	0	0	0	6(-6)	2	Delay				
	28	Concrete of Stair	2	2(-2)	0	0	3(-3)	0	0	0	0	0	2	Delay				
	25	Concrete of Floor	1	5(-5)	0	0	6(-6)	0	0	0	0	0	1	Delay				
195	50	Landscaping		5	0	0	4	2	0	0	0	0	12	Continue				
	49	Fence and Gate		4(-1)+1	2	1+4	5(-1)+1	2	2	0	0	1	10	Continue	194	2STW=1LAB, 2STW=1PLT	47	34 35 36 40
	46	Interior Painting		2(-2)+2	0	0	0	5(-1)+1	0+2	0+4	0	0	10	Continue	194	2WEL=1LAB, 2ROF=1LAB, 2ROF=1PAT	43 45	34 35 36 40
	44	Wooden Floor		1(-1)+1	3	0+2	0	0	0	0	0	0	10	Continue	194	2STW=1LAB	37	34 35 36 40
	48	Receptacles and Switches	7	1(-1)+1	0	0	0	0	0	0	0+2	3	7	Finish		2PLB=1LAB		
	36	Stud and Lintel	7	1(-1)	3(-3)	2(-2)	2(-2)	0	0	0	0	0	7	Delay				
	40	Ceiling Work	5	1(-1)	2(-2)	0	2(-2)	0	0	0	0	0	5	Delay				
	35	Plumbing Fixtures	4	2(-2)	0	0	0	0	0	0	5(-2)	0	4	Delay				
	34	HVAC	2	2(-2)	0	0	0	0	0	0	0	6(-4)	2	Delay				
	28	Concrete of Stair	2	2(-2)	0	0	3(-3)	0	0	0	0	0	2	Delay				
	25	Concrete of Floor	1	5(-5)	0	0	6(-6)	0	0	0	0	0	1	Delay				
193	50	Landscaping		5	0	0	4	2	0	0	0	0	12	Continue	192		47	28
	48	Receptacles and Switches		1	0	0	0	0	0	0	0	3	7	Continue				
	36	Stud and Lintel	7	1	3	2	2	0	0	0	0	0	7	Finish				
	40	Ceiling Work	5	1	2	0	2	0	0	0	0	0	5	Finish				
	35	Plumbing Fixtures	4	2(-2)+2	0	0+4	0	0	0	0	5	0	4	Finish		4STW=2LAB		
	34	HVAC	2	2(-2)+2	0	0	0	0+6	0+4	0	0	6(-3)+3	2	Finish	192	4PAT=2LAB, 2PAT=1ELE, 4WEL=2ELE	32 33	28 47
	28	Concrete of Stair	2	2(-2)	0	0	3(-3)	0	0	0	0	0	2	Delay				
	25	Concrete of Floor	1	5(-5)	0	0	6(-6)	0	0	0	0	0	1	Delay				
30	5	Formwork of Footing	10	3	5	0	0	0	3	0	0	0	10	Finish	21		3	
	6	Rebar of Footing	10	3	0	6	0	0	0	0	0	0	10	Finish	21		3	
20	3	Excavation	5	5	1	0	0	0	0	0	0	0	5	Finish	16		1 2	
15	2	Piling	15	6	0	3	2	0	0	0	0	0	15	Finish				
	1	Site Preparation	10	5(-3)+3	2+4	2+2	3	3	3	0	2	2	10	Finish	6	4CAR=2LAB, 2STW=1LAB		
5	2	Piling		6	0	3	2	0	0	0	0	0	15	Continue	1			

Table 4. Results from the first and the second steps

ID	Activity	Duration (days)	Step 1: initial solution				Step 2: resource-constrained float		
			Forward-pass		Backward-pass		Forward-pass		Resource-constrained float
			Early Start (a)	Early Finish (b)	Late Start (c)	Late Finish (d)	Early Start (e)	Early Finish (f)	(e – c or f – d)
1	Site Preparation	10	0	10	5	15	0	10	5
2	Piling	15	0	15	0	15	0	15	0
3	Excavation	5	15	20	15	20	15	20	0
4	Underground Utility	7	15	22	52	59	52	59	0
5	Formwork of Footing	10	20	30	20	30	20	30	0
6	Rebar of Footing	10	20	30	20	30	20	30	0
7	Concrete of Footing	7	30	37	30	37	30	37	0
8	Formwork of Ground Column	9	37	46	48	57	37	46	11
9	Rebar of Ground Column	6	37	43	51	57	37	43	14
10	Concrete of Ground Column	2	46	48	57	59	54	56	3
11	Formwork of Ground Beam	15	37	52	37	52	37	52	0
12	Rebar of Ground Beam	12	37	49	40	52	37	49	3
13	Concrete of Ground Beam	2	52	54	55	57	52	54	3
14	Termite Protection	2	54	56	57	59	54	56	3
15	Backfill	10	56	66	59	69	59	69	0
16	Formwork of Column	20	66	86	69	89	69	89	0
17	Rebar of Column	15	66	81	79	94	69	84	10
18	Concrete of Column	7	86	93	157	164	141	148	16
19	Formwork of Beam	20	86	106	89	109	89	109	0
20	Rebar of Beam	15	81	96	94	109	84	99	10
21	Concrete of Beam	7	106	113	109	116	109	116	0
22	PC Floor	5	113	118	175	180	168	173	7
23	Formwork of Floor	3	120	123	181	184	173	176	8
24	Rebar of Floor	2	118	120	180	182	173	175	7
25	Concrete of Floor	1	123	124	184	185	176	177	8
26	Formwork of Stair	10	113	123	179	189	163	173	16
27	Rebar of Stair	7	113	120	182	189	175	182	7
28	Concrete of Stair	2	123	125	189	191	184	186	5
29	Roof Trusses	15	93	108	164	179	148	163	16
30	Roof Sheathing	5	108	113	179	184	163	168	16
31	Masonry Wall	25	116	141	116	141	116	141	0
32	Ductwork	3	113	116	185	188	177	180	8
33	Electrical System	5	113	118	184	189	176	181	8
34	HVAC	2	118	120	191	193	191	193	0
35	Plumbing Fixtures	4	120	124	189	193	182	186	7
36	Stud and Lintel	7	141	148	186	193	177	184	9
37	Plastering Work	20	141	161	141	161	141	161	0
38	Wall Ceramic Tile	15	141	156	146	161	141	156	5
39	Floor Ceramic Tile	15	141	156	146	161	141	156	5
40	Ceiling Work	5	156	161	188	193	179	184	9
41	Door	7	156	163	161	168	161	168	0
42	Window	8	156	164	195	203	191	199	4
43	Drywall	15	161	176	161	176	161	176	0
44	Wooden Floor	10	161	171	193	203	193	203	0
45	Cabinet and Counters	8	163	171	168	176	168	176	0
46	Interior Painting	10	176	186	193	203	193	203	0
47	Exterior Painting	15	176	191	176	191	176	191	0
48	Receptacles and Switches	7	176	183	188	195	184	191	4
49	Fence and Gate	10	191	201	193	203	193	203	0
50	Landscaping	12	191	203	191	203	191	203	0
	Project cost (THB)		2,946,400		2,918,950		2,946,400		

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3.2 Step 2: resource-constrained float

A forward-pass calculation results in a different critical path than the initial solution (backward-pass calculation). Therefore, it is necessary to use the same resource relationship during reverse calculation to guarantee the same critical path. A forward-pass calculation is performed again using this concept (Table 5).

Table 5 illustrates that the eligible activities of each decision-making stage are sorted by activity priority on the basis of the earliest backward start rule, which states that an earliest backward start activity leads to higher activity priority. For example, at the beginning of the project (day 1), resources are first assigned to piling (backward start on day 1), which has more priority than site preparation (backward start on day 6).

On day 16, the only eligible activity is excavation. Underground utility should in fact be considered an eligible activity at this decision-making stage but not because it has the resource relationship with formwork of ground beam and rebar of ground beam. As a result, underground utility must be started after the completion time of formwork of ground beam and rebar of ground beam (successors of excavation), and it is not possible to take place with excavation concurrently. This process is then continued until all activities are scheduled. Finally, forward-pass scheduling is completed with a project duration of 203 days and a project cost of 2,946,400 THB.

Table 4 also presents the results of the second step. It can be seen that the project cost of a backward-pass calculation is lower than that of a forward-pass calculation; thus, the initial solution is still a backward-pass calculation.

3.3 Step3: optimal resource replacement

3.3.1 Manual adjustment

The algorithm used in this study shifts noncritical activities within their resource-constrained float to reduce previous resource replacement and decrease project cost. However, all strategies eventually produce a schedule that is between an early start schedule and a late start schedule. Critical activities remain unchanged, whereas noncritical activities are shifted within their resource-constrained float without any project delays. Furthermore, the activities have sequence and resource relationships; therefore, shifting one activity has a domino effect on the other activities.

Applying the shifting algorithm to the initial solution leads each cycle to reduce resource replacement, thus decreasing project cost. A detailed analysis is presented in the following:

Cycle 1: A three-day backward shift of rebar of ground beam can reduce the replacement of plasterer by six units, painter by twelve units, roofer by four units and plumber by two units on days 50-52. Although this can increase the replacement of steel worker by six units on days 50-52, the effect of decreasing cost from reducing the replacement of plasterers, painters, roofers and plumbers is greater than that increasing cost from steel workers. Accordingly, the project cost can be reduced by 9,500 THB (2,918,950 THB to 2,909,450 THB).

Cycle 2: A two-day backward shift of rebar of ground column can reduce the replacement of painter and roofer by sixteen units and four units on day 56-57, respectively. Although this can increase the replacement of steel worker by eight units on day 56-57, the effect of decreasing cost from reducing the replacement of painters and roofer is greater than that increasing cost from steel workers. Accordingly, the project cost can be additionally reduced by 7,200 THB (2,909,450 THB to 2,902,250 THB).

Cycle 3: A five-day backward shift of wall ceramic tile can reduce the replacement of labor by two units, carpenter by two units, steel worker by eight units and painter by thirty-two units on days 157-161. Accordingly, the project cost can be additionally reduced by 15,400 THB (2,902,250 THB to 2,886,850 THB).

Cycle 4: A four-day backward shift of floor ceramic tile can reduce the replacement of carpenter and steel worker by sixteen units on day 158 – 161. Accordingly, the project cost can be further reduced by 5,200 units (2,886,850 THB to 2,881,650 THB).

It should be noted that further shifting the remaining activities does not improve the solution of the current schedule; therefore, minimum resource scheduling is achieved.

3.3.2 Optimisation adjustment

An integer programming model is developed to verify resource replacement in the resource-constrained float of the initial solution. The decision variable $x_{(i,\ t)}$ indicates whether activity i starts on day t. The value is one if activity i can start on day t; otherwise, the value is zero. The start time of activity i is defined by the decision variable $s_{(i)}$. The last decision variable $y_{(r,\ m,\ t)}$ determines the number of insufficient resources r replaced by qualified resource m on day t. The objective function (2) attempts to minimise the project cost, including the resource cost (3), indirect cost (4), and penalty cost (5). Equation (6) indicates that each activity has only one start date. Accordingly, the start time of each activity is determined by (7). Furthermore, the activity must be started at an early start time (8) and late start time (9). The sequence and resource relationships between a pair of activities ensures that a successor activity cannot be started until all predecessor activities are completed (10). The number of qualified resources used to replace the insufficient resource is proportional to the decision variable $y_{(r,\ m,\ j)}$ (11). Equation (12) ensures that the resource availability constraint is met.

Objective function: minimise $(C_r + C_i + C_p)$, (2)

which is subjected to:

$$C_r = \sum_{t=1}^{t_p} \sum_{i=1}^{k} \left(q_{(i,\ r)} \cdot x_{(i,\ t)} - \sum_{m=1}^{l_{(m,\ r)}} y_{(r,\ m,\ t)} + \sum_{s=1}^{h_{(s,\ r)}} z_{(r,\ s,\ t)}\right) \cdot u_{(r)};\ \forall r = 1, \ldots, p, \quad (3)$$

$$C_i = v \cdot t_p, \quad (4)$$

Table 5. Forward-pass calculation using resource relationship of initial solution

Time	ID	Activity	Backward Start	Resource LAB	CAR	STW	PLT	PAT	WEL	ROF	PLB	ELE	Duration	Decision	Forward Finish	Resource Replacement	Sequence Relationship	Resource Relationship
				8	6	7	8	8	5	5	5	6						
1	2	Piling	0	6	0	3	2	0	0	0	0	0	15	Start				
	1	Site Preparation	5	5(-3)+3	2+4	2+2	3	3	3	0	2	2	10	Start	10	4CAR=2LAB, 2STW=1LAB		
11	2	Piling		6	0	3	2	0	0	0	0	0	15	Continue	15			
16	3	Excavation	15	5	1	0	0	0	0	0	0	0	5	Start	20		1 2	
21	5	Formwork of Footing	20	3	5	0	0	0	3	0	0	0	10	Start	30		3	
	6	Rebar of Footing	20	3	0	6	0	0	0	0	0	0	10	Start	30		3	
31	7	Concrete of Footing	30	5	0	0	5	0	0	0	0	0	7	Start	37		5 6	
38	11	Formwork of Ground Beam	37	3	5	0	0	0	3	0	0	0	15	Start			7	
	12	Rebar of Ground Beam	40	4	0	6	0	0	0	0	0	0	12	Start			7	
	8	Formwork of Ground Column	48	2(-1)+1	4(-3)+3	0	0+8	0+2	3(-1)+1	0	1	1	9	Start		2PLT=1LAB, 6PLT=3CAR, 2PAT=1WEL	7	
	9	Rebar of Ground Column	51	2(-2)+2	0	5(-4)+4	0	0+6	0	0+4	0+2	0	6	Start	43	4PAT=2LAB, 2PAT=1STW, 4ROF=2STW, 2PLB=1STW	7	
44	11	Formwork of Ground Beam		3	5	0	0	0	3	0	0	0	15	Continue				
	12	Rebar of Ground Beam		4	0	6	0	0	0	0	0	0	12	Continue				
	8	Formwork of Ground Column		2(-1)+1	4(-3)+3	0	0+2+6	0+2	3(-1)+1	0	1	1	9	Continue	46	2PLT=1LAB, 6PLT=3CAR, 2PAT=1WEL		
47	11	Formwork of Ground Beam		3	5	0	0	0	3	0	0	0	15	Continue				
	12	Rebar of Ground Beam		4	0	6	0	0	0	0	0	0	12	Continue	49			
50	11	Formwork of Ground Beam		3	5	0	0	0	3	0	0	0	15	Continue	52			
53	4	Underground Utility	52	3	2	3	2	0	2	0	5	4	7	Start			1 2	11 12
	13	Concrete of Ground Beam	55	4	0	0	5	0	0	0	0	0	2	Start	54		11 12	
55	4	Underground Utility		3	2	3	2	0	2	0	5	4	7	Continue				
	10	Concrete of Ground Column	57	3	0	0	4	0	0	0	0	0	2	Start	56		8 9	13
	14	Termite Protection	57	5(-3)+3	0+4	0+2	0	0	0	0	0	0	2	Start	56	4CAR=2LAB, 2STW=1LAB	13	8 9
192	34	HVAC	191	2	0	0	0	0	0	0	0	6	2	Start	193		32 33	28 47
	50	Landscaping	191	5	0	0	4	2	0	0	0	0	12	Start			47	28
	42	Window	195	2(-1)+1	2+2	0	0	0	0	0	0	0	8	Start		2CAR=1LAB	38 39	48
194	50	Landscaping		5	0	0	4	2	0	0	0	0	12	Continue				
	42	Window		2	2	0	0	0	0	0	0	0	8	Continue	199			
	44	Wooden Floor	193	1	3	0	0	0	0	0	0	0	10	Start			37	34 35 36 40
	46	Interior Painting	193	2(-2)+2	0	0+4	0	5	0	0	0	0	10	Start		4STW=2LAB	43 45	34 35 36 40
	49	Fence and Gate	193	4(-4)+4	2(-1)+1	1+2	5(-1)+1	2(-1)+1	2+2	0+4	0+4	1+2	10	Start		2STW=1LAB, 2WEL=1LAB,	47	34 35 36 40
200	50	Landscaping		5	0	0	4	2	0	0	0	0	12	Continue	203			
	44	Wooden Floor		1	3	0	0	0	0	0	0	0	10	Continue	203			
	46	Interior Painting		2	0	0	0	5	0	0	0	0	10	Continue	203			
	49	Fence and Gate		4(-4)+3+1	2	1+6	5(-1)+1	2(-1)+1	2+2	0+2+2	0	1	10	Continue	203	6STW=3LAB,		

$$C_p = w \cdot \max\{t_p - t_c, 0\}, \quad (5)$$

$$\sum_{t=ES_{(i)}+1}^{LS_{(i)}} x_{(i,\, t)} = 1;\ \forall i = 1,\ldots, k, \quad (6)$$

$$s_{(i)} = \left(\sum_{t=ES_i+1}^{LF_i} x_{(i,\, t)} \cdot t\right) - 1;\ \forall i = 1,\ldots, k, \quad (7)$$

$$s_{(i)} \geq ES_{(i)}, \quad (8)$$

$$s_{(i)} \leq LS_{(i)}, \quad (9)$$

$$s_{(i)} + d_{(i)} \leq s_{(j)};\ \forall (i, j) \in A, \quad (10)$$

$$z_{(m,\, r,\, t)} = n \cdot y_{(r,\, m,\, t)}, \quad (11)$$

$$\sum_{i=1}^{n} \sum_{t=ES_{(i)}+1}^{LS_{(i)}} \left(q_{(i,\, r)} \cdot x_{(i,\, t)} - \sum_{m=1}^{l_{(m,\, r)}} y_{(r,\, m,\, t)} + \sum_{s=1}^{h_{(s,\, r)}} z_{(r,\, s,\, t)}\right) \cdot V_{(i,\, t)} \leq R_{(r)};\ \forall i = 1,\ldots, k;\ \forall r = 1,\ldots, p, \quad (12)$$

$x_{(i,\, t)} = 1$; if activity i starts on day t,

0; otherwise and $t \leq ES_i$ and $t > LS_i + 1$, (13)

$$s_{(i)} = \text{integer}, \quad (14)$$

$$y_{(r,\, m,\, t)} = \text{integer}, \quad (15)$$

where C_r is the total resource cost; C_i is the total indirect cost; C_p is the total penalty cost; $s_{(i)}$ is the start date of activity i; t_p is the project duration; t_c is the contract duration; $u_{(r)}$ is the daily cost of resource r; v is the daily indirect cost; w is the daily penalty cost; $q_{(i,\, r)}$ is the daily requirement of resource r for activity i; $y_{(r,\, m,\, t)}$ is the number of resources r replaced by qualified multiskilled resource m on day t; $z_{(r,\, s,\, t)}$ is the number of resources r used to replace insufficient resource s on day t; k is the last activity in project network; p is the last resource type r; $l_{(m,\, r)}$ is the last qualified multiskilled resource m that can replace resource r; $h_{(s,\, r)}$ is the last insufficient resource s that can be replaced by resource r; $ES_{(i)}$ is the early start of activity i; $LS_{(i)}$ is the late start of activity i; $d_{(i)}$ is the duration of activity i; A is the set of pair of activities with a sequence relationship or resource relationship; $V_{(i,\, t)}$ is the vector containing 1s at position t, t+1,…, $t+d_i$-1; $R_{(r,\, t)}$ is the available resource r on day t; and $R_{(r)}$ is the row vector of resource r that has $R_{(r,\, t)}$.

Table 6. The results of a real-world project case study

Approach	Project Duration	Project cost	Cost saving
MS project	270 days	2,988,900 THB	4%
Existing heuristic approach	203 days	2,946,400 THB	2%
MCM algorithm	203 days	2,881,650 THB	-

To apply the proposed integer programming model to the project case study, an open source Excel add-in called OpenSolver is used as the solver tool. The scheduling and project cost solutions are generated by this tool. It can be seen that solutions from the optimisation adjustment do not differ from manual adjustment.

4. REAL-WORLD PROJECT CASE STUDY ANALYSIS

The MCM algorithm was applied to real-world project case study. The results for the project cost obtained by the MCM algorithm are compared with the results from Microsoft project (Commercial project management software) and the existing heuristic approach (Table 6). Since Microsoft Project uses the core concept of the single-skilled resource scheduling where the critical activities with insufficient resources may be delayed regardless of the resource replacement. Therefore, it results in longer project duration than the multiskilled resource scheduling. According to the practical level, especially in the large-scale project, delaying project duration is not affect only increasing the indirect cost and the penalty cost, but also the opportunity cost of moving the resources to new construction project. Furthermore, increasing cost from delaying project duration (indirect cost, penalty cost and opportunity cost) is mostly greater than that increasing cost from resources replacement. Therefore, it is reasonable to state that the MCM algorithm and existing multiskilled resource scheduling can create the results of shorter project duration and lower project cost comparing with Microsoft project (single-skilled resource scheduling). Besides, the results indicate that the MCM algorithm was able to guarantee a lower project cost than the existing heuristic approach because the core concept of the MCM algorithm is the reduction of the resource replacement cost of the initial solution. The initial solution is selected from the lowest project cost among a forward-pass calculation (existing heuristic approach) and backward-pass calculation (proposed calculation method). Furthermore, the manual calculation of the MCM algorithm guarantees the generation of optimal solutions, as verified by optimisation adjustment of which the solutions do not differ.

5. CONCLUSION

This study proposes an alternative heuristic approach for multiskilled resource scheduling. The proposed MCM algorithm is simple and can be calculated manually. It provides a solution that is superior to that of the optimisation approach in the optimal resource replacement step. Furthermore, its advantages can be practically applied in large projects that demand a large number of activities and resources. As demonstrated by real-world project case study, the MCM algorithm guarantees the minimum project cost of resource scheduling.

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