Optimizing the Utilization of Shareable Equipment in Multiple Shifts for Construction Projects

Dho Heon Jun[1], Choong-Hee Han*[2] and Dae-Jin Kim[3]

[1] CEO, Bluegeny, Co., Seongnam, Gyeonggi, Republic of Korea
[2] Professor, Department of Architectural Engineering, Kyung Hee University, Republic of Korea
[3] Assistant Professor, Department of Architectural Engineering, Kyung Hee University, Republic of Korea

Abstract

Construction equipment is often shared among many construction projects. In a real construction project, supply of this critical equipment is often limited, which often generates negative impacts on project performance. Multiple shifts are very effective and efficient for achieving schedule acceleration while resolving resource conflicts among project activities for shareable equipment. This paper presents a novel multiple-equipment shift-scheduling model that is capable of optimizing the utilization of critical and shareable construction equipment in multiple shifts for construction projects. The model is designed to help construction planners identify and generate optimal shift work plans and schedules that can simultaneously minimize the project duration and total shareable equipment utilization cost while complying with all of the availability constraints. An example is analyzed to illustrate the use of the present model and demonstrate its new and unique capabilities in optimizing equipment utilization in multiple shifts for construction projects.

Keywords: resource allocation; acceleration; equipment; scheduling; optimization

1. Introduction

Network scheduling techniques identify the duration required to perform a construction project under the assumption of an unlimited supply of construction resources. However, in practice, the supply of these construction resources are often limited due to seasonal shortages, equipment breakdowns, competing demands, delayed deliveries as well as a large amount of associated uncertainty (Clough *et al.*, 2000). Especially, the utilization of heavy, cost intensive and specialized equipment is often restricted due to the lack of availability and expensive utilization cost. Accordingly, construction planners and schedulers need to take into consideration various alternatives to effectively utilize this limited number of critical equipment on site in order to minimize its negative impact on project performance. These alternatives include rescheduling activities, subcontracting, working overtime and on weekends, and multiple shifts.

Multiple shifts are very effective and efficient for achieving schedule acceleration while resolving resource conflicts among project activities for shareable equipment by enabling their daily utilization to double or triple (Clough *et al.*, 2000; Oexman *et al.*, 2002). Moreover, the equipment may be utilized for twice as many hours per day with the same daily rental cost (Rojas, 2008), and thereby could significantly reduce the cost for their utilization (e.g., heavy and cost intensive equipment) in construction projects. In Fig.1., a simple example is given that utilizes a limited amount of shareable equipment in multiple shifts as well as its impacts on project performance. As shown in Fig.1.(B), early scheduling of this project causes a resource conflict between activities A and B for the same equipment, and thereby the project duration should be extended by delaying one of the activities to resolve this resource conflict, as shown in Fig.1.(C). In order to avoid such an extension in project duration and simultaneously resolve these resource conflicts, there are two alternatives to multiple-shift operations, as shown in Figs.1.(D) and (E): (1) reducing each activity duration by operating two shifts per day and resolving conflicting equipment demands by delaying one of activities until another activity releases the same equipment, as shown in Fig.1.(D); or (2) assign each activity to a different shift (e.g., assign activity A to the day shift and activity B to the evening shift) to avoid the conflicting equipment demands between them and reduce the project duration by scheduling those two activities on the same day, as shown in Fig.1.(E).

However, as shown in Figs. 1(D) and (E), the impacts of these alternatives on project duration and total equipment utilization cost are different. As such, a construction planner needs to evaluate and identify all feasible shift work plans and schedules for project activities in order to accomplish schedule acceleration with a cost effective equipment utilization plan.

A number of studies were conducted to investigate and optimize the utilization of construction resources to maximize project performance using various optimization techniques, such as heuristic methods, mathematical programming, and meta-heuristic methods. These existing studies can be classified into two main categories based on their objectives and constraints: (1) minimizing the project time and/ or cost without complying with resource availability constraints (Antill and Woodhead, 1990; El-Rayes and Kandil, 2005; Feng *et al.*, 1997; Xiong and Kuang, 2008); and (2) minimizing the project time and/or cost while complying with resource availability constraints and improving resource utilization (Chan *et al.*, 1996; Hegazy, 1999; Jaskowski and Sobotka, 2006; Kim and Ellis, 2008; Moussourakis and Haksever, 2004). Despite the significant research efforts and contributions of the above models, none of them have focused on optimizing the utilization of critical and shareable construction equipment in multiple shifts for construction projects in order to accomplish schedule acceleration while minimizing the utilization cost.
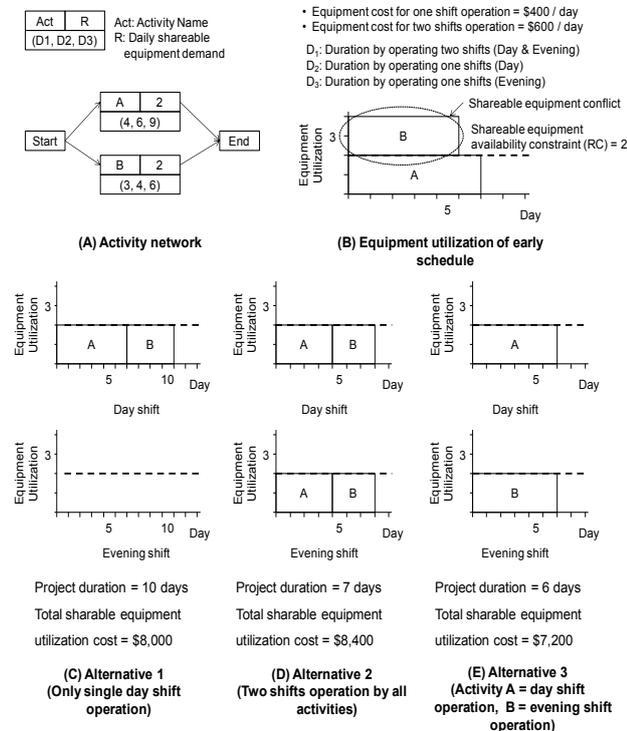

Fig.1. Impact of Utilizing Shareable Equipment in Multiple Shifts on Project Performance

This paper presents a novel multiple-equipment shift-scheduling model that is capable of optimizing the utilization of critical and shareable construction equipment in multiple shifts for construction projects in order to accomplish schedule acceleration and provide the most cost effective equipment utilization plan. This model is designed to help construction planners identify and generate optimal shift work plans and schedules that can simultaneously minimize the project duration and total shareable equipment utilization cost while complying with all of the availability constraints.
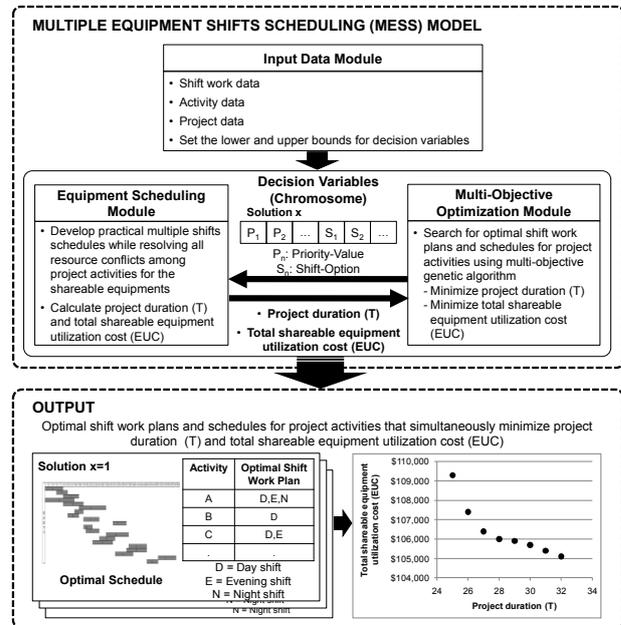

Fig.2. The Multiple-equipment Shift-scheduling (MESS) Model and its Output

2. Multiple-Equipment Shift-Scheduling (MESS) Model

The primary objective of this multiple-equipment shift-scheduling (MESS) model is to simultaneously minimize project duration (T) and total shareable equipment utilization cost (EUC) while complying with all availability constraints of the critical and shareable equipment. To this end, the MESS model is developed in three main modules: (1) the input data module that retrieves all relevant input data and sets lower and upper bounds for decision variables; (2) the equipment scheduling module that develops practical multiple-shift schedules while resolving all resource conflicts among project activities for the shareable equipment; and (3) the multi-objective optimization module that searches for optimal shift work plans and schedules for project activities that can simultaneously minimize the project duration (T) and total shareable equipment utilization cost (EUC), as shown in Fig.2. The following sections describe these three main modules in more detail.

3. Input Data Module

The main objective of this module is to retrieve all relevant input data specified by the construction

planner for multiple shifts scheduling and to set lower and upper bounds for the optimization decision variables. The input data for the project activities can be classified into four main categories as follows:

3.1 Shift Work Data

This shift work input data consists of the specified type of shift system (SS) used for the project (e.g., SS=1: one-shift system, SS=2: two-shift system, and SS=3: three-shift system); and the feasible shift-options (S_n) for utilizing a multiple-shift operation for each activity (n) for the specified type of shift system. Table 1. illustrates the typical shift systems that can be utilized in construction projects (Helander, 1981). As shown in Table 1., according to the combination of day, evening, and night shifts, each type of shift system has a different number of feasible options to utilize multiple-shifts for each activity. Each of these feasible shift options has different work hours and production rates (Popescu *et al.*, 2003), thereby leading to a unique activity duration. This procedure is illustrated in Table 2.

Table 1. Feasible Shift Option for Two- and Three-shift Systems

Shift-Option (S_n)	Two-shift system (SS=2)	Work hours/day	Three-shift system (SS=3)	Work hours/day
0	Two shifts (Day & Evening Shifts)	15.5 hrs	Three shifts (Day, Evening, & Night shifts)	22.5 hrs
1	One shift (Day shift)	8 hrs	Two shifts (Day & Evening shifts)	15.5 hrs
2	One shift (Evening shift)	7.5 hrs	Two shifts (Day & Night shifts)	15 hrs
3	-		Two shifts (Evening & Night shifts)	14.5 hrs
4	-		One shift (Day shift)	8 hrs
5	-		One shift (Evening shift)	7.5 hrs
6	-		One shift (Night shift)	7 hrs

Typical shift work periods:	Equipment shift premium cost (RSMeans 2001)
Day shift: 8:00 AM − 4:30 PM,	Two-shift cost = 150% of one-shift cost
Evening shift: 4:30 PM − 12:30 AM	Three-shift cost = 200% of one-shift cost
Night shift: 12:30 AM − 8:00 AM	

3.2 Activity Data

This input data can be classified into two types of input data, activity duration data and shareable equipment cost data.

1) Activity duration data: This includes the duration (D_{Sn}) for each feasible shift-option (S_n) of a given activity (n). The productivity during nighttime construction often decreases due to worker fatigue, health disorders, social life disruption, lower morale, and higher accident rates (Helander, 1981; Kogi, 1985).

In order to provide a more reliable estimate of the project duration, a construction planner can adjust the duration of each feasible shift-option (S_n) for the project activities by reflecting the productivity loss caused by shift work, based on the historical productivity data or the one that is recommended by the Mechanical Contractors Association of America (MCAA) Labor Estimating Manual. The manual recommends increasing the man-hours for evening shifts by 20% and for night shifts by 30% (Kitchens, 1996).

2) Shareable equipment cost data: This includes the daily cost rate ($EC_{k,y}$) of shareable-type (k) equipment for one-, two-, and three-shift operations. The present model is designed to allow a construction planner to reflect the premium cost for the utilization of shareable-type (k) equipment in multiple shifts by differentiating the daily equipment cost rate ($EC_{k,y}$) based on the number of shifts (y) that the type (k) equipment utilized per day. For example, the daily equipment cost rates for a two-shift (y=2) operation is 150% higher than that of a one-shift (y=1) operation, while a three-shift (y=3) operation is 200% higher than a one-shift (RSMeans, 2001), because utilizing equipment for longer hours requires additional costs,

Table 2. Feasible Shift-options for Activity and the Associated Activity Duration

Activity (n)	Shift-option (S_n)	Feasible shift options	Duration (D_{Sn})	Daily shareable-type (k) equipment demand on shift (j) ($r_{n,k,j,Sn}$) Type (k=1)	
				Day shift (j=1)	Evening shift (j=2)
A	0	Two shifts (Day & Evening shifts)	4	2	2
	1	One shift (Day shift)	6	2	0
	2	One shift (Evening shift)	8	0	2
B	0	Two shifts (Day & Evening shifts)	3	1	1
	1	One shift (Day shift)	5	1	0
	2	One shift (Evening shift)	7	0	1

Type (k=1) of equipment cost for a one shift operation ($EC_{1,1}$) = \$400/day

Type (k=1) of equipment cost for a two shifts operation ($EC_{1,2}$) = \$600/day

such as maintenance and operation costs. The present model assumes that the same crew formation is utilized in every shift for a multiple-shift operation.

3.3 Project Data

This input data includes precedence relationships among project activities, as well as shareable-type (k) equipment availability constraints (RC_k). The present model assumes that all types of shareable equipment can be utilized in every shift: day, evening, and night shifts.

After retrieving all of the relevant data, the input data module sets the lower and upper bounds of two decision variables, the priority-value (P_n) and the shift-option (S_n), as shown in Equations (1) and (2). The priority-value determines the scheduling sequences for project activities to resolve resource conflicts among the project activities for the shareable equipment. On the other hand, the shift-option (S_n) represents the feasible shift options of utilizing a multiple-shift operation for a given activity (n). These two decision variables are represented using a genetic algorithm chromosome and are designed to generate all possible project schedules and equipment utilizations for multiple shifts, as shown in Fig.2.

$$0 \le P_n \le N\text{-}1, \tag{1}$$

$$0 \le S_n \le UBS_n\text{-}1, \tag{2}$$

where UBS_n is the total number of feasible shift options for an activity (n) based on the type of shift system (SS), and N is the total number of activities in the project.

(A) Activity network

(B) Decision Variables

Shift-option (S_n): S_A =1, S_B = 0
Priority-Value (P_n): P_A = 1, P_B = 0

$RC_1 = 2$

(C) Cycle X before shifting activity A

(D) Cycle X+1 after shifting activity A
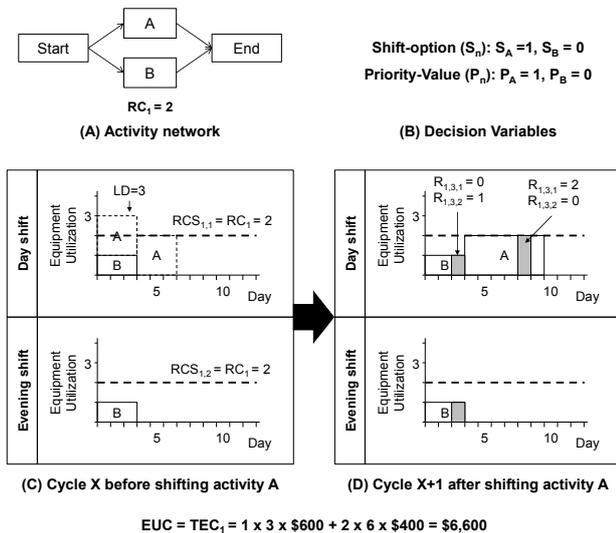
EUC = TEC_1 = 1 x 3 x $600 + 2 x 6 x $400 = $6,600

Fig.3. Activity Schedule Based on the Decision Variables, S_n and P_n

4. Equipment Scheduling Module

The objective of this module is to develop a practical multiple-shift schedule that complies with the job logic of the project activities and resolves the resource conflicts among project activities for the shareable equipment. This module is designed to calculate the

project duration (T) and total shareable equipment utilization cost (EUC) for the developed multiple-shift schedule based on two decision variables, the priority-value (P_n) and the shift-option (S_n). The computation procedure in this module is performed using the following three main steps:

- Step 1: Create an activity scheduling sequence array (A[m]) based on the priority-values (P_n) that are generated by the multi-objective optimization model. The serial method proposed by Kelly (1963) is employed in this step to generate various activity scheduling sequences while complying with precedence relationships among the project activities. This method was utilized in many studies regarding resource constrained scheduling problems (Jun and El-Rayes, 2009, 2010; Kim and Ellis, 2008). The procedure of this method is described in more detail in the study conducted by Jun and El-Rayes (2010).

- Step 2: Schedule each activity (n) based on the activity scheduling sequence array (A[m]) and shift-option (S_n) while complying with all shareable-type equipment availability constraints (RC_k). The computation procedure can be performed using the following nine sub-steps:

I. Set the resource constraint ($RC_{k,j}$) for each shareable-type (k) equipment on each shift (j) using Equation (3). Since the present model assumes that all shareable types of equipment can be possibly utilized in any type of shift (j), the resource constraint ($RCS_{k,j}$) imposed on each shift (j) should be equal to each type (k) of equipment availability constraint (RC_k). For the example shown in Fig.3., which utilizes the activity data in Table 2., the total available amount of shareable-type (k=1) equipment is 2 (RC_1=2), and accordingly the resource constraint ($RCS_{1,j}$) imposed on the day (j=1) and evening (j=2) shifts should be equal to RC_1=2;

$$RCS_{k,j} = RC_k \qquad j=1,2,3, \tag{3}$$

where j is the type of shift (e.g., j=1: day shift, j=2: evening shift, and j=3: night shift).

II. Set m=0 and select the first activity (n) in the activity scheduling sequence array A[m].

III. Calculate the early start time (ES_n) and early finish time (EF_n) for the selected activity (n) based on its duration specified by the shift-option (S_n), as shown in Equations (4) and (5).

$$ES_n = \max_{n` \in PRE_n} \{EF_{n`}\} + 1 , \tag{4}$$

$$EF_n = ES_n + D_{S_n} - 1 , \tag{5}$$

where PRE_n is the set of immediate predecessors of the activity (n), and D_{Sn} is the duration of activity (n) under the shift-option (S_n).

IV. Allocate the type (k) of shareable equipment on the shift (j) specified by the shift-option (S_n) of the activity (n). As shown in Fig.3., the multi-objective

optimization module generates the shift-option (S_B) for activity B as S_B=0, which specifies a two-shift operation (i.e., operating with day and evening shifts) as shown in Table 2. Accordingly, the shareable-type (k=1) equipment for activity B is allocated to each day and evening shift.

V. Set m=m+1 and select the next activity (n) in the activity scheduling sequence array A[m].

VI. Calculate the early start time (ES_n) and early finish time (EF_n) for the selected activity (n) using Equations (4) and (5).

VII. Calculate the daily demands of all shareable-type (k) equipment on the shift (j) during the period ranging from the early start time (ES_n) to the early finish time (EF_n) of the activity (n).

VIII. Find the latest day (LD) that an activity (n) has conflicting shareable equipment demands with other already scheduled activities during the period ranging from its early start time (ES_n) to its early finish time (EF_n). The daily demand of each type (k) of equipment on shift (j) during that period should be carefully checked to see if they violate any resource constraints ($RCS_{k,j}$) imposed on each shift (j). If the activity (n) can be scheduled without violating any of the resource constraints ($RCS_{k,j}$) imposed on each shift (j), then proceed to sub-step IX. Otherwise, recalculate the early start time ($ES_{n'}$) and early finish time ($EF_{n'}$) for the activity (n) using Equations (6) and (7), and repeat the steps from sub-steps VII to VIII until the activity (n) can be scheduled without violating any of the resource constraints ($RCS_{k,j}$) imposed on each shift (j). The example shown in Fig.3. illustrates the procedure of resolving resource conflicts among project activities for the shareable equipment using the latest day (LD). The example utilizes the activity data shown in Table 2. It is assumed that activities A and B share the same type of shareable equipment (e.g., k=1) for their works, and that only two types (k=1) of equipment are available on site (RC_1=2). As shown in Fig.3., activity A cannot start on the same day as activity B due to the resource constraints imposed on the day and evening shifts. The latest day (LD) for activity B that violates the resource constraint ($RSC_{1,1}$=2) is the 3rd day, and thereby activity A should be rescheduled to start on the day following the 3rd day (i.e., the 4th day).

$$ES_n` = LD + 1 , \qquad (6)$$

$$EF_n` = ES_n` + D_{S_n} - 1 . \qquad (7)$$

IX. Repeat the procedures from sub-steps V to VIII for the remaining activities in the project.

- Step 3: Calculate the project duration (T) and total shareable equipment utilization cost (EUC) for the revised project schedule using Equations (8) and (9). The present model is designed to calculate the total shareable equipment utilization cost (EUC) based on the number of shifts (y) that shareable-type (k) equipment had utilized on each day (t). To this end, first

the amount of shareable-type (k) equipment utilized in one (y=1), two (y=2), and three (y=3) shifts on each day (t) ($R_{k,t,y}$) should be identified. For the example shown in Fig.3.(D), only one shareable-type (k=1) equipment is utilized in two shifts (y=2) on the 3rd day (t=3) ($R_{1,3,2}$ = 1). However, none of the shareable-type (k=1) equipment are utilized in only one shift (y=1) on the 3rd day (t=3) ($R_{1,3,1}$ = 0). On the other hand, all of the available two shareable-type (k=1) equipment are utilized in one shift (y=1) on the 8th day (t=8) ($R_{1,8,1}$ = 2). Therefore, none of them are utilized in two shifts (y=2) on the 8th day (t=8) ($R_{1,8,2}$ = 0). After identifying the total amount of shareable-type (k) equipment utilized ($R_{k,t,y}$) in one, two, and three shifts on each day (t), the total shareable-type (k) equipment utilization cost (TEC_k) can be calculated using Equation (10), as shown in Fig.3. As stated earlier, construction planners can consider the premium cost for shareable-type (k) equipment by adjusting their daily cost rate ($EC_{k,y}$) based on the number of shifts utilized per day for the type (k) of equipment, as shown in Equation (10). For example, the daily equipment cost rates for two shifts can be 150% higher than for one shift, and three shifts is 200% higher than for one shift (RSMeans, 2001).

$$T = \underset{n \in \text{All}}{\text{Max}} \{EF_n\} , \qquad (8)$$

$$EUC = \sum_{K=1}^{K} TEC_k , \qquad (9)$$

$$TEC_k = \begin{cases} \sum_{t=1}^{T} (R_{k,t,1} \cdot EC_{k,1} + R_{k,t,2} \cdot EC_{k,2} + R_{k,t,3} \cdot EC_{k,3}) & \text{if } SS=3 \\ \sum_{t=1}^{T} (R_{k,t,1} \cdot EC_{k,1} + R_{k,t,2} \cdot EC_{k,2}) & \text{if } SS=2 \end{cases} . \quad (10)$$

The above three main steps are repeated for each solution in the population of each generation in the multi-objective optimization module. The calculated values of those two objective functions (i.e., minimizing the project duration (T) and total shareable equipment utilization cost (EUC)) are then used as the fitness values for each solution to reproduce new offspring solutions in subsequent generations during the search for optimal/near optimal solutions. After a number of predetermined generations, each solution in the final population represents an optimal/near optimal shift work plan and schedule for project activities that simultaneously minimize the project duration (T) and total shareable equipment utilization cost (EUC) while complying with all of the availability constraints for shareable-type (k) equipment (RC_k).

5. Multi-Objective Optimization Module

The primary objective of this module is to search for and identify optimal/near optimal shift work plans and schedules for project activities that can simultaneously minimize the project duration and cost. To achieve this, a multi-objective genetic algorithm (Deb *et al.*,

2001) is implemented in the present model. This algorithm adopts the concept of Pareto optimality to enable multi-objective optimization, and it utilizes the survival of the fittest criteria to evolve solutions over a number of specified generations. The algorithm starts with generating an initial set of random solutions (i.e., the initial parent population), and then these solutions evolve toward better solutions by repeating the following three main steps: (1) a fitness evaluation step that evaluates the fitness of each chromosome (i.e., the decision variables) of the population based on the objective functions (e.g., the project duration (T) and total shareable equipment utilization cost (EUC), as shown in Equations (8) and (9)); (2) a reproduction step that selects the most fit solutions in the parent population based on the fitness criteria, Pareto optimal rank, and crowding distance for each solution, which are then used to produce new offspring (i.e., the child population) by using the genetic operators of crossover and mutation; and (3) an elitism step that evaluates the fitness of a new child population and generates a new parent population by combining the parent and child populations and selecting the best 50% of the solutions from the combined population. This elitism step preserves the best solutions of the parent population over generations (Deb *et al.*, 2001). These three main steps are repeated over a number of predetermined generations and generate a Pareto optimal set of non-dominated solutions for multi-objective optimization problems. Whenever the fitness of each solution is evaluated, as shown in Fig.2., the equipment scheduling module is used to schedule project activities and calculate the project duration (T) and total shareable equipment utilization cost (EUC) based on the decision variables generated in this module. The calculated values of two objective functions, the project duration (T) and total shareable equipment utilization cost (EUC), are then used in this module to evaluate the fitness of each solution and evolve them toward better solutions.

6. Application Example

An example is analyzed to illustrate the use of the present model and demonstrate its capabilities. The example includes 15 activities that have start to finish relationships among them, as shown in Fig.4. It is assumed that every shift requires the same crew formation to perform the activities in the project, and all types of shareable equipment can be utilized in every day, evening, and night shifts. Two types (k=1 and k=2) of shareable equipment were considered in the present model to optimize their utilization in multiple shifts in order to minimize the project duration and their utilization cost. It is assumed that the availability of these two types of equipment is limited to $RC_1=2$ and $RC_2=3$.

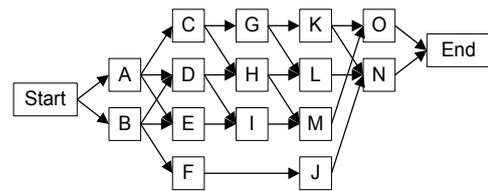Early schedule of this project based on a single day-shift (one-shift) operation requires 38 days of project

Fig.4. Activity Network

Project duration (T) = 38 days
Total shareable equipment utilization cost (EUC) = \$122,400

(A) Shareable type (k=1) equipment utilization

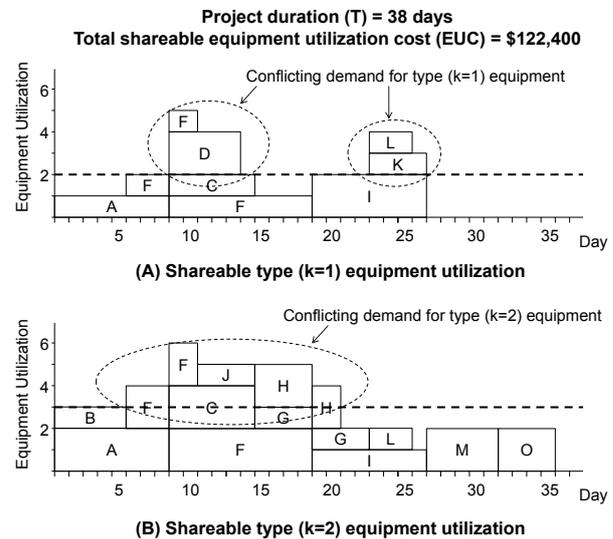**(B) Shareable type (k=2) equipment utilization**

Fig.5. Equipment Utilization of an Early Schedule Using a Single Day-shift Operation (One Shift System)

duration and \$122,400 of total shareable equipment utilization cost (EUC). In this schedule, as shown in Fig.5., a maximum of five types of shareable (k=1) equipment and six types of shareable (k=2) equipment are required with 38 days of project duration, as shown in Table 3. An MS-project was used to resolve these conflicting equipment demands, and it generated 57 days of project duration. In order to reduce the project duration of an early schedule, first, the early schedule was accelerated by operating two shifts for all activities. The schedule of operating two shifts for all activities generated 23 days for the project duration and \$114,900 for the total shareable equipment utilization cost (EUC). However, this schedule requires a maximum of five shareable types (k=1) of equipment and six shareable types (k=2) of equipment, where neither of them satisfy the equipment availability constraints. The conflicting equipment demands among project activities were resolved by using an MS-project, and it generated 36 days for the project duration (Simple solution 1), as shown in Table 3. Second, the early schedule was accelerated by operating three shifts for all activities, and then the conflicting equipment demands were resolved by an MS-project. The MS-project generated 27 days for the project duration and \$114,400 for the total shareable equipment utilization cost (EUC) (Simple solution 2), as shown in Table 3. It should be noted that total shareable equipment utilization cost (EUC) could be reduced in the schedules that operate with two and
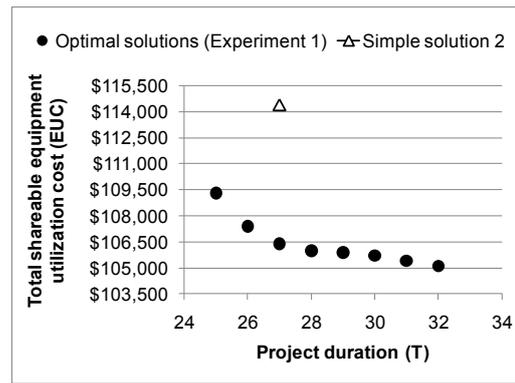
Dho Heon Jun

Table 3. Simple Solutions

Solutions	Project Duration (T)	Total shareable equipment utilization cost (EUC)	Maximum required amount of shareable-type (k=1) equipment	Maximum required amount of shareable-type (k=2) equipment
Early schedule (One shift)	38 days	$122,400	5	6
Early schedule (Two shifts)	23 days	$114,900	5	6
Early schedule (Three shifts)	18 days	$114,400	4	5
MS-Projects (One shift)	57 days	$122,400	2	3
MS-Projects (Two shifts) **Simple solution 1**	36 days	$114,900	2	3
MS-Projects (Three shifts) **Simple solution 2**	27 days	$114,400	2	3

(A) Experiment 1: Three shifts system (SS=3)

(B) Experiment 2: Two shifts system (SS=2)

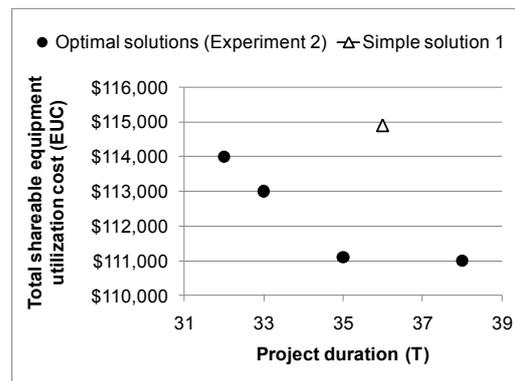Fig.6. Optimal Tradeoff Solutions for Two Experiments

three shifts for the project activities, because operating two and three shifts can reduce the equipment utilization cost by enabling the work hours to double or triple the cost of single day-shift operation.

In order to illustrate the new capabilities of the present model for generating optimal solutions that minimize the project duration and total shareable equipment utilization cost (EUC) while complying with equipment availability constraints, the present model with two objective functions (i.e., the minimized project duration (T) and total shareable equipment utilization cost (EUC), shown in Equations (8) and (9)) were used to analyze the example. Two experiments were conducted to analyze the impact of each two- (SS=2) and three-shift (SS=3) system on project performance.

In the first experiment, a three-shift system (SS=3) was considered to accelerate the schedule. All feasible shift-options (S_n) were analyzed by the present model. The minimum project duration achieved in this experiment was 25 days and its total shareable equipment utilization cost (EUC) was $109,300, as shown in Fig.6.(A). This solution outperforms Simple solution 2 generated by the MS-project in terms of both the project duration and the total shareable equipment utilization cost, as shown in Fig.6.(A).

The second experiment was conducted to analyze the impact of a two-shift system (SS=2) on project performance. Only the shift-options (S_n) that belong to the two-shift system (i.e., S_n=1, 4, and 5) were set as S_n=0, 1, and 2 respectively. The optimization results of this experiment are shown in Fig.6.(B). The minimum project duration achieved in this experiment was 32 days and its total shareable equipment utilization cost (EUC) was $114,000. This solution outperforms Simple solution 1 generated by the MS-project in terms of both the project duration and the total shareable equipment utilization cost, as shown in Fig.6.(B). Computation times to obtain the results in Fig.6.(A) and Fig.6.(B) are approximately six and four hours, respectively. Each of the generated Pareto optimal solutions identifies the optimal shift work plans and schedules for each activity that can simultaneously minimize the project duration and total shareable equipment utilization cost (EUC).

Two experiments clearly illustrate that the present model has the capability to optimize the utilization of critical and shareable construction equipment using multiple shifts for construction projects and to help construction engineers and planners in identifying optimal shift work plans and schedules for each activity. This simultaneously minimizes the project duration and total shareable equipment utilization cost (EUC) while complying with all of the shareable equipment availability constraints.

7. Summary and Conclusions

A multiple-equipment shift-scheduling (MESS) model was developed to support a construction planner by optimizing the utilization of critical and shareable construction equipment in multiple shifts for construction projects. The model is designed to help construction planners identify and generate optimal shift work plans and schedules that can simultaneously minimize the project duration and total shareable equipment utilization cost while complying with all of the availability constraints. To this end, an optimization model was developed using three modules: (1) an input data module; (2) an equipment scheduling; and (3) a multi-objective optimization module. An application example was analyzed to illustrate the use of the present model and demonstrate its capabilities in generating optimal tradeoff solutions between minimizing the project duration and total shareable equipment utilization cost (EUC). Two experiments were conducted to illustrate the impacts of both two- and three-shift systems on project performance. The results of analysis in each experiment clearly illustrate the new capabilities of the present model in producing optimal tradeoff solutions between minimizing the project duration and minimizing the total shareable equipment utilization cost (EUC), where each solution identifies the optimal shift work plans and schedules for each activity while complying with every type of shareable equipment availability constraint. These new and unique capabilities should prove useful to construction planners and are expected to improve the existing scheduling practices for construction projects.

Acknowledgement

References

1) Antill, J. M., and Woodhead, R. W. (1990) Critical path methods in construction practice. Wiley-IEEE.
2) Chan, W. T., Chua, D. K. H., and Kannan, G. (1996) Construction resource scheduling with genetic algorithms. Journal of Construction Engineering and Management, 122(2), pp.125-132.
3) Clough, R. H., Sears, G. A., and Sears, S. K. (2000) Construction project management. John Wiley and Sons.
4) Deb, K., Pratap, A., Agrawal, S., and Meyarivan, T. (2001) A fast and elitist multi-objective genetic algorithm: NSGA-II. KANGAL Report 200001, Genetic Algorithm Laboratory, Indian Institute of Technology, Kanpur, India.
5) El-Rayes, K., and Kandil, A. (2005) Time-cost-quality trade-off analysis for highway construction. Journal of Construction Engineering and Management, 131(4), pp.477-486.
6) Feng, C., Liu, L., and Burns, S. A. (1997) Using genetic algorithms to solve construction time-cost trade-off problems. Journal of Computing in Civil Engineering, 11(3), pp.184-189.
7) Hegazy, T. (1999a) Optimization of construction time-cost trade-off analysis using genetic algorithms. Canadian Journal of Civil Engineering, 26(6), pp.685-697.
8) Helander, M. (Ed.). (1981) Human factors/ergonomics for building and construction. JOHN WILEY & SONS Inc., New York.
9) Jaskowski, P., and Sobotka, A. (2006) Scheduling construction projects using evolutionary algorithm. Journal of Construction Engineering and Management, 132(8), pp.861-870.
10) Jun, D. H., and El-Rayes, K. (2009) Multi-objective optimization of resource scheduling in construction projects. 2009 Construction Research Congress, Seattle, Washington, pp.82-82.
11) Jun, D. H., and El-Rayes, K. (2010) Optimizing the utilization of multiple labor shifts in construction projects. Automation in Construction, 19(2), pp.109-119.
12) Kelly, J. E. (1963) The Critical-path Method: Resource planning and scheduling, in: J.F. Muth, G.L. Thompson (Eds.). Industrial Scheduling, Prentice Hall, NJ.
13) Kim, J., and Ellis, J. (2008) Permutation-based elitist genetic algorithm for optimization of large-sized resource-constrained project scheduling. Journal of Construction Engineering and Management, 134(11), pp.904-913.
14) Kim, J., and Ellis, R. D. (2008) Permutation-based elitist genetic algorithm for optimization of large-sized resource-constrained project scheduling. Journal of Construction Engineering and Management, 134(11), p.904.
15) Kitchens, M. (1996) Estimating and project management for building contractors. ASCE Publications.
16) Kogi, K. (1985) Temporal factors in work scheduling. Introduction to the problems of shiftwork, Hours of Work, S. Folkard and T. H. Monk, eds., John Wiley & Sons, New York.
17) Moussourakis, J., and Haksever, C. (2004) Flexible model for time/cost tradeoff problem. Journal of Construction Engineering and Management, 130(3), pp.307-314.
18) Oexman, R. D., Knotts, T. L., and Koch, J. (2002) Working while the world sleeps: a consideration of sleep and shift work design. Employee Responsibilities and Rights Journal, 14(4), pp.145-157.
19) Popescu, C., Phaobunjong, K., and Ovararin, N. (2003) Estimating building costs. CRC Press.
20) Rojas, E. M. (2008) Construction productivity: a practical guide for building and electrical contractors. J. Ross Publishing.
21) RSMeans. (2001) Building construction cost data: 59th annual edition. Kingston, Mass.
22) Xiong, Y., and Kuang, Y. (2008) Applying an ant colony optimization algorithm-based multiobjective approach for time--cost tradeoff. Journal of Construction Engineering and Management, 134(2), pp.153-156.