Journal of Civil Engineering and Management
ISSN 1392-3730 / eISSN 1822-3605
2022 Volume 28 Issue 7: 590–600
https://doi.org/10.3846/jcem.2022.17204

SELECTING HIGH PRIORITY ACTIVITIES FOR THE REALLOCATION OF RESOURCES TO REDUCE CONSTRUCTION DURATION

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Received 22 December 2021; accepted 11 May 2022

Abstract. It is difficult to identify economically feasible alternatives to reduce the duration of construction, as many important factors are present in any given construction project, such as increased construction costs and incentives and decreased delay liquidated damages. Most importantly, thousands of activities are interconnected in a complicated manner. This study proposes a method for analyzing the priority of activities for the reallocation of resources in order to reduce construction delay duration. The proposed method is composed of two steps: the prioritization of activities that can reduce construction duration and a reallocation of resources based upon that prioritization. First, in order to analyze priority, combinations of the lowest-cost activities for reducing per day are derived. Then, the importance of influence factors is analyzed, using the fuzzy analytic hierarchy process and fuzzy inference, and priority is derived based on the importance level. Next, the resources are reallocated based on the objective functions of maximizing the importance of the selected activities, reducing the duration, and minimizing the reducing cost. Decision-makers can compare between the reduction duration and available cost, and compare between results of the proposed method and the existing cost-slope method. Then, decision-makers can use the proposed method differently based on their own preferences toward economic and qualitative importance.

Keywords: reallocation of resources, priority of activities, delay liquidated damages, fuzzy analytic hierarchy process, fuzzy inference.

Introduction

The size of delay liquidated damages (DLDs) increases when the size of a project is large or when its stakeholders are numerous. The benefit of reducing the contracted duration is great because a change in construction duration impacts the product output, such as a semiconductor, for instance, in case of a plant project. Thus, the level of duration reduction is determined by considering the reduced DLDs and the increased incentives as well as the increased cost for the duration reduction, as one objective of a duration reduction is to improve the economics.

When the reduction duration is increased, the change to economic feasibility is large. The number of critical paths (CP) is also notably increased because the construction project entails thousands of activities that are organically interrelated. The number of activities that need to be taken into consideration is reduced, compared with the start and middle stages, because decisions about whether or not to reduce the duration are generally made at a later stage of the project. Nevertheless, due to the number of activities and the complicated interconnected relationships, decision-making can be difficult, even in the latter stages. This study proposes a method for the prioritization of those interrelated activities, taking DLDs, incentives, construction costs, and duration into consideration in order to reduce delays. Then, a method is also proposed for the reallocation of resources based on the analyzed priority.

Previous studies did not include the characteristics of activities such as the relation between activities (García-Nieves et al., 2019; Haj & El-Sayegh, 2015; Liu & Wang, 2011). This study derives combinations of the lowest-cost activities for reduction per day. Next, the influence factors for duration reduction are derived and the importance of the factors are analyzed, and then a method is proposed for analyzing the priority of activities based on the importance of factors. Lastly, the method for the reallocation of

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resources is proposed based on the priority assigned to these activities as well as minimized reduction cost.

This study consists of three steps. First, previous studies related to the reduction of construction duration and the reallocation of resources are reviewed, and their differences in relation to this study are explained. Next, the research model is explained including the method for selecting of the lowest-cost activities, the method for analyzing the importance of influence factors for resource reallocation, and the method for reallocating the resource. For analyzing the lowest-cost activities, this study proposed the method and explained in Section 2.1. For analyzing the importance, fuzzy analytic hierarchy process (AHP) and fuzzy inference are used. Fuzzy AHP is used for analyzing the importance of influence factors and fuzzy inference is used for analyzing the importance of factors for each activity. The results of fuzzy AHP are weighted for analysis of fuzzy inference. Fuzzy AHP represents a combination of the AHP and fuzzy theory that it is used for mitigating the uncertainty that depends on professionalism, credibility, and inaccurate linguistic expression of evaluators (Ilbahar et al., 2022; N. Prascevic & Z. Prascevic, 2017; Yilmaz et al., 2022). AHP is used for the importance analysis of targets by relative comparison (Yazdani-Chamzini, 2014; Zhou et al., 2019, 2020). Fuzzy inference establishes rules and deduces another uncertain statement from uncertain statements based on the fuzzy theory (Lee et al., 2018; Asadi et al., 2018). To reallocate the resources, this study proposes a method of analyzing the reducible construction duration and the reduction cost per day using three objective functions: maximizing the importance of the activities, reducing the duration, and minimizing the reducing cost. Finally, the applicability of the proposed method is analyzed through a case study.

1. Literature review

Previous studies have proposed methods for reallocating resources in order to reduce construction duration, including the time-cost trade-off problem (García-Nieves et al., 2019; Haj & El-Sayegh, 2015; Issa et al., 2019; Lin & Lai, 2020; Liu & Wang, 2011). García-Nieves et al. (2019) proposed a method to use scheduling properties, benefits, and challenges for solving the time-cost trade-off problem of repetitive activities' scheduling. Haj and El-Sayegh (2015) proposed a method to reduce the total float using a nonlinear-integer programming model. This integer programming method analyzed the goal value when the variable is an integer. Huang et al. (2016) proposed a method for solving the time-cost tradeoff problem by minimizing the required cost when the work sequences were changed in repetitive work. Issa et al. (2019) proposed a risk model for the qualitative and quantitative analysis of cost overruns and construction duration delays using a fuzzy logic tool. Lin and Lai (2020) proposed a method for analyzing the time–cost tradeoff based on genetic algorithms (GAs), taking changes in crew productivity into consideration. These previous studies have evaluated activities based on cost, time, and reallocated resources. However, the reallocation of resources is influenced by other characteristics of activities in addition to cost and time. Liu and Wang (2011) proposed a selection method for a project that is based on profit as well as cost. They also proposed solving the time-dependent scheduling problem for each project under limited resources. However, their proposed method was to select projects not activities. This study proposes a method for analyzing the priority of activities for resource reallocation using various influence factors, as well as cost, which impact the reallocation of resources.

Several previous studies have proposed finding the critical path (CP) after deriving the influence on activities as well as cost and time factors (Castro-Lacouture et al., 2009; Dorfeshan et al., 2018; Zammori et al., 2009). Dorfeshan et al. (2018) analyzed the influence level of time, cost, risk, quality, and safety factors and proposed a method to determine the CP. Zammori et al. (2009) derived duration variability, cost, shared resources, risk of major design revisions, and external risk as influence factors in complex projects and analyzed the CP using fuzzy logic and multi criteria decision-making. Castro-Lacouture et al. (2009) proposed a method for determining the construction schedule using a fuzzy model and for completing projects within a minimum amount of time when resources, such as time and cost, are insufficient. These previous studies are similar to the present study because they analyze the influence of various factors on schedule management; however, the factors themselves were not used as the resource reallocation criteria as they are here.

Previous studies have also proposed methods for reducing construction duration by overlapping activities (Bogus et al., 2011; Moon et al., 2015; Srour et al., 2013). Bogus et al. (2011) analyzed the changes to potential risk when construction duration and cost are reduced through concurrent engineering for fast-track and rework construction. Moon et al. (2015) identified overlapping activities and analyzed the overlapping risk using the fuzzy theory and proposed a method to minimize those overlapping activities that have a high risk using generic algorithm (GA). The GA is often used for complex problems when the data are insufficient or conventional statistical and mathematical methods are inadequate. Srour et al. (2013) proposed a method for scheduling based on information exchange between activities, including task duration, when overlapping activities are selected for fast-tracking the design step. These previous studies have all proposed methods to select activities for reducing the duration and reallocating the resources, which is similar to the intention of this study. However, this study analyzes and applies influence factors for the reallocation of resources, as well as for the overlapping of activities, which is what makes this study different from the others described above. In addition, this study also proposes a method for reallocating resources based on the priority of activities.

In summary, the previous studies used various methods, such as GA, to address the time-cost tradeoff problem. For the time-cost tradeoff problem, the GA's performance has been verified by previous studies, but because a construction project includes thousands of activities, the problem's resolution time using GA is greater than when a conventional calculation method is used. The previous studies did not also include the influence factors related to construction duration reduction. Similarly, although several previous studies derived and analyzed these influence factors, they did not apply them to the reallocation of resources. In light of the thousands of interrelated activities involved in a construction project, this reallocation is a difficult task. The method proposed in this study simplifies the reallocation by analyzing the priority of the activities based on influence factors related to reducing the duration of the construction.

2. Research model

This study proposes a method for analyzing the priority of activities for resource reallocation and for reallocating resources based on this priority (Figure 1). First, the cost-slope of the activities is calculated, and then the lowest-cost activities are selected. The influence of the factors on resource reallocation is also identified, and the importance of the factors is analyzed using fuzzy AHP. The analysis assigns importance to the factors for each activity through weighting and fuzzy inference is applied based on the calculated value. Thus, the priority of activities for the reallocation of resources is derived.

Next, after reducible construction duration and reduction cost per day are calculated, resources are reallocated. For resource reallocation, a day is reduced from reducible duration and then identifies target duration are all reduced. If so, then resource reallocation is completed and economic analysis is conducted. If not, then construction duration is reduced by another day. Under available resources, the analysis process is repeated until all target duration is reduced. After the resource reallocation is completed, the economic analysis is conducted, including the increased required costs and incentives and the reduced DLDs. Finally, the result of economic analysis is compared with the results of the existing cost slope and the difference is identified. Decision-makers can determine whether or not to use the proposed method depending on economic analysis.

2.1. Method of selecting the lowest-cost activities

The existing cost slope method calculates the reduction cost per day of CP activities and reallocates resources in order of lower the cost activity. When a project includes thousands of activities, the number of CP are greatly increased if one day is reduced. Thus, selecting the lowest-cost activities in order to reduce project duration by one day is difficult.

This study proposes a method of selecting the lowest-cost activities to reduce the project duration by one day (Figure 2). First, the lowest-cost activities are identified for each CP and are arranged into combinations, such as combination (1) in Figure 2. Combinations can include duplicated activities, as each CP can include the same the lowest-cost activity. If the derived activities are not duplicated through combination, another combination is derived to contain duplicate low-cost activities, such as combination (2) in Figure 2. The daily reduction in cost is then compared between combinations (1) and (2). If the cost of combination (1) is lower than that of combination (2), combination (1) is selected to reduce the project duration. Otherwise, combination (2) is selected as preferential, and is then compared with another combination of three lowest-cost activities, such as combination (3) in Figure 2. Again, the reduction costs per day of combinations (2) and (3) are compared. If the cost of combination (2) is lower than that of combination (3) because the daily reduction in the cost of activity (c) is three times higher than that of activity (b) and activities (d) and (e) are more than zero, then combination (2) is selected to reduce the project's duration. Otherwise, combination (3) is selected as preferential. The process is repeated until the cost of the previous combination is less than the cost of the current combination.

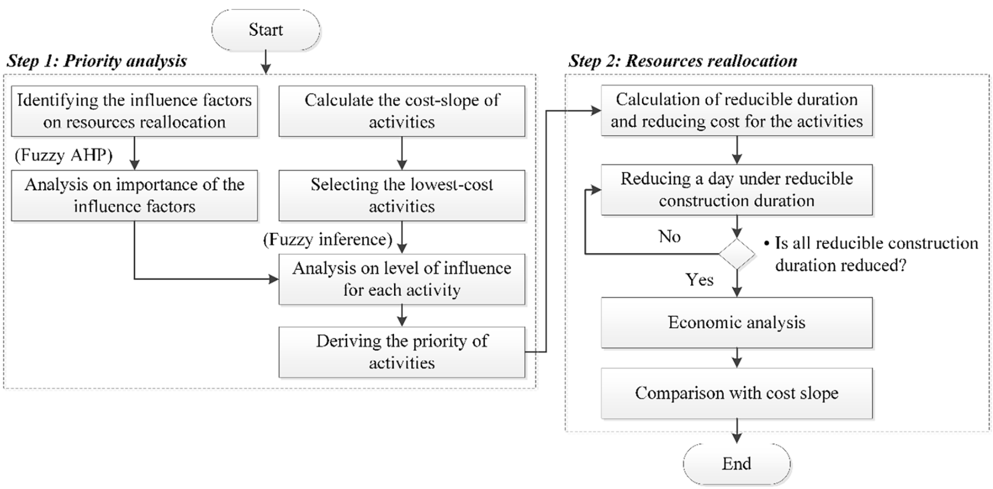

Figure 1. Research model

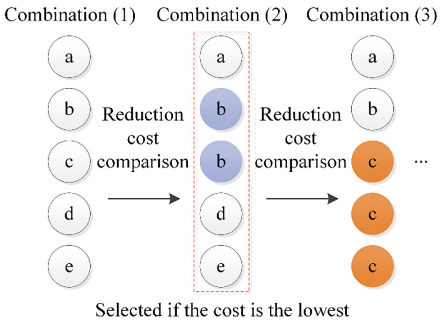

Figure 2. Example of how to select the lowest-cost activities

2.2. Influence factors on resources reallocation

This section aims to identify the influence factors on resource reallocation while satisfying quality, safety, and environmental requirements. The approval of extension of time (EOT) is determined based on who is responsible for delayed causes – e.g., contractor or owner. The evaluation criteria for the approval possibility of the EOT are derived based on a previous study (El-adaway et al., 2018) and on the International Federation for Consulting Engineers' (FIDIC) silver book (Federation Internationale Des Ingineurs Conseile [FIDIC], 1999). The criteria derived are divided into: delay by contractor, owner, concurrent delay, and force majeure. The delays caused by contractors include work error, rework by omission, negligence of duties, and management failure of the subcontractor. The delays caused by owners include owner's demand for work temporary pause and delay of owner's mandatory. Damage from concurrent delay is shared, depending on the responsibility ratio, because both owners and contractors are responsible for this type of delay. The causes of a force majeure delay are typically acts of God (such as bad weather or other natural disasters), riots, and impossible construction processes. It is difficult to approve the EOT if a contractor is responsible for causing the delay and, in such cases, the contractor takes responsibility for the damages, typically. Thus, this study excludes the delay by contractor as a sub-criteria for the EOT possibility evaluation.

The overlapping method is used for fast tracking, although an excessive overlapping of activities has a bad influence on work (Wang et al., 2016). Several previous studies have analyzed possibly reducing construction duration by overlapping. When activities are selected for overlapping, a dependency of activities, work complexity, and rework should be considered (Ammar, 2013; Moon et al., 2015; Srour et al., 2013).

Some existing studies have also explained the importance of activity repetition (Huang et al., 2016). Repetition of activity can improve work productivity because repetition has a learning effect on workers. Hence, this study considers work productivity to be a selection factor for resource allocation activities. Many previous studies have derived influence factors from productivity. Among these factors, those related to force majeure are excluded; then, they are divided into those for the procurement of skilled workers and materials (Mirahadi & Zayed, 2016) and for the special or large equipment needs (Durdyev et al., 2018). This study determines the influence factors as the characteristics of work crew, equipment, and procurement.

In summary, the influence factors for resource reallocation activities are the EOT approval possibility, the overlapping activities possibility, and work productivity (Table 1). The sub-factors of EOT are owner's liability, concurrent delay, and force majeure. The sub-factors of overlapping activities are their dependency and complexity, while the sub-factors of work productivity are the crew, procurement, and equipment characteristics.

2.3. Weighting analysis based on fuzzy AHP

Fuzzy AHP is used for the analysis of the importance of influence factors on resource reallocation. The triangular fuzzy number is used due to its usability and application in mathematics for construction risk (Polat et al., 2017; Zhou et al., 2018). Fuzzy AHP is applied in two steps.

First, after influence factors are derived, pair-wise comparisons are conducted between the factors. The factors analyzed are: the reduction cost per day, the EOT approval possibility, the overlapping possibility, and work productivity (Table 1). For example, when the evaluation scale has five points, the evaluated value is represented as an interval not a constant value. The triangular fuzzy membership number is $T_i = (l_i, m_i, h_i)$ and the pair-wise comparison results between activities are represented as $T_{ij} = (l_{ij}, m_{ij}, h_{ij})$, where, i and j are influence factors. The importance of activity i is represented as $W_i = (l_i, m_i, h_i)$ and the value is calculated by geometric average value of the pair-wise comparison (Eqn (1)). Pair-comparison means that "a" is more important than "b" about "n" times. Namely, geometric average value is used as the average value for the pair-comparison because the interval deviation is increased by "n" times and not a constant value.

Table 1. The resource reallocation influence factors

Factors	Sub-factors
EOT	Owner's liability
	Concurrent delay
	Force majeure
Overlapping	Dependency of activities
	Complexity of activities
Work productivity	Characteristics of work crew
	Procurement
	Equipment

$$W_i = \sum_{j=1}^{m} T_{ij} \times \left(\sum_{i=1}^{n}\sum_{j=1}^{m} T_{ij}\right)^{-1}; \quad (1)$$

$$\sum_{j=1}^{m} T_{ij} = \left(\sum_{j=1}^{m} l_{ij}, \sum_{j=1}^{m} m_{ij}, \sum_{j=1}^{m} h_{ij}\right);$$

$$\sum_{i=1}^{n}\sum_{j=1}^{m} T_{ij} = \left(\sum_{i=1}^{n}\sum_{j=1}^{m} l_{ij}, \sum_{i=1}^{n}\sum_{j=1}^{m} m_{ij}, \sum_{i=1}^{n}\sum_{j=1}^{m} h_{ij}\right).$$

Next, the calculated importance (W_i) of activities is compared and then the possibility of "$W_i = (l_i, m_i, h_i) \geq W_j = (l_j, m_j, h_j)$" is calculated through Eqn (2). The minimum value is selected from the calculated values (Eqn (3)) and then the importance of factors is determined.

$$P\left(W_i \geq W_j\right) = 1, if\ m_i \geq m_j; \tag{2}$$

$$P\left(W_i \geq W_j\right) = \frac{l_i - h_j}{\left(m_j - h_j\right) - \left(m_i - l_i\right)},\ \text{if}\ u_i \geq l_j;$$

$$P\left(W_i \geq W_j\right) = 0,\ \text{otherwise}$$

$$\min P\left(W_i \geq W_1, W, \ldots, W_n\right), i = 1, 2, \ldots, n. \tag{3}$$

2.4. Priority analysis based on fuzzy inference

Fuzzy inference is used to evaluate the importance of each activity. Fuzzy inference is a rule based system for deducing conclusions using the "if–then" rule. The basic rule of fuzzy inference (Eqn (4)) is that of a dual-input single-output system, where the input value is more than two and the output value is one (Lee et al., 2018).

$$\text{If } x \text{ is } A_k \text{ and } y \text{ is } B_k, \text{ then } z \text{ is } C_k. \tag{4}$$

Among several fuzzy inference methods, Mamdani's max-min method and the center-of-gravity method are used. First, the degree of compatibility (w) is analyzed (Eqn (5)). The $\mu_A(x)$ is membership function for indicating whether element x is included in set A. Then, the max-min method derives a maximum value from among the minimum values (Eqn (7)) after calculating a minimum value between "A" and "B" (Eqn (6)). The center-of-gravity method is used to change the calculated fuzzy values into constant values (Eqn (8)).

$$w = \min\{\mu_A(x), \mu_B(y)\}; \tag{5}$$

$$\mu_{Ck}(z) = \min\{w, \mu_{Ck}(z)\}; \tag{6}$$

$$\mu_C(z) = \max\{\mu_{Ck}(z), \mu_{C(k+n)}(z)\}; \tag{7}$$

$$z_* = \frac{\int z \cdot \mu_c(z)dz}{\int \mu_c(z)dz}. \tag{8}$$

For example, if two rules and membership functions, and x is 2 and y is 7, the result of fuzzy inference is calculated as follows (Figure 3):

Rule$_1$: If x is A_1 (high) and y is B_1 (*high*), then z is C_1 (high);

Rule$_2$: If x is A_2 (middle) and y is B_2 (middle), then z is C_2 (middle).

First, the degree of compatibility is calculated using (Eqn (5)). The value of Rule$_1$ (w_1) and Rule$_2$ (w_2) are analyzed as 0.25 and 0.75, respectively, because the minimum value between $\mu_A(x)$ and $\mu_B(y)$ is derived:

$$w_1 = \mu_A(x) \wedge \mu_B(y) = 0.25 \wedge 0.7 = 0.25;$$

$$w_2 = \mu_A(x) \wedge \mu_B(y) = 0.85 \wedge 0.75 = 0.75.$$

Next, the minimum values between the degree of compatibility (w_n) and output of fuzzy inference are calculated using Eqn (6), and then the maximum value of the minimum values are analyzed using Eqn (7).

Lastly, the result of fuzzy inference is converted to constant value using Eqn (8). A denominator is an area of the analyzed output (C_{n*}) and the calculations of definite integral are as follows. In result, the output of fuzzy inference is 6.94.

$$\int \mu_c(z)dz = \left\{\frac{1}{2} \times (2 - 1.5) \times 0.25)\right\} + \{(10 - 2) \times 0.25\} + \left\{(7.5 - 6) \times (0.75 - 0.25) \times \frac{1}{2}\right\} + \{(10 - 7.5) \times (0.75 - 0.25)\} = 3.69;$$

$$\int z \cdot \mu_c(z)dz = \int_{1.5}^{2} (\frac{1}{2} \times 0.25) z\,dz + \int_{2}^{10} (0.25) z\,dz + \int_{6}^{7.5} \left(\frac{1}{2} \times 0.5\right) z\,dz + \int_{7.5}^{10} (0.5) z\,dz = 25.58;$$

$$z_* = \frac{25.58}{3.69} = 6.94.$$

Based on influence factors for fuzzy inference, 125 rules are created (Table 2). For example, if the possibility of EOT and overlapping are very high (VH), and work

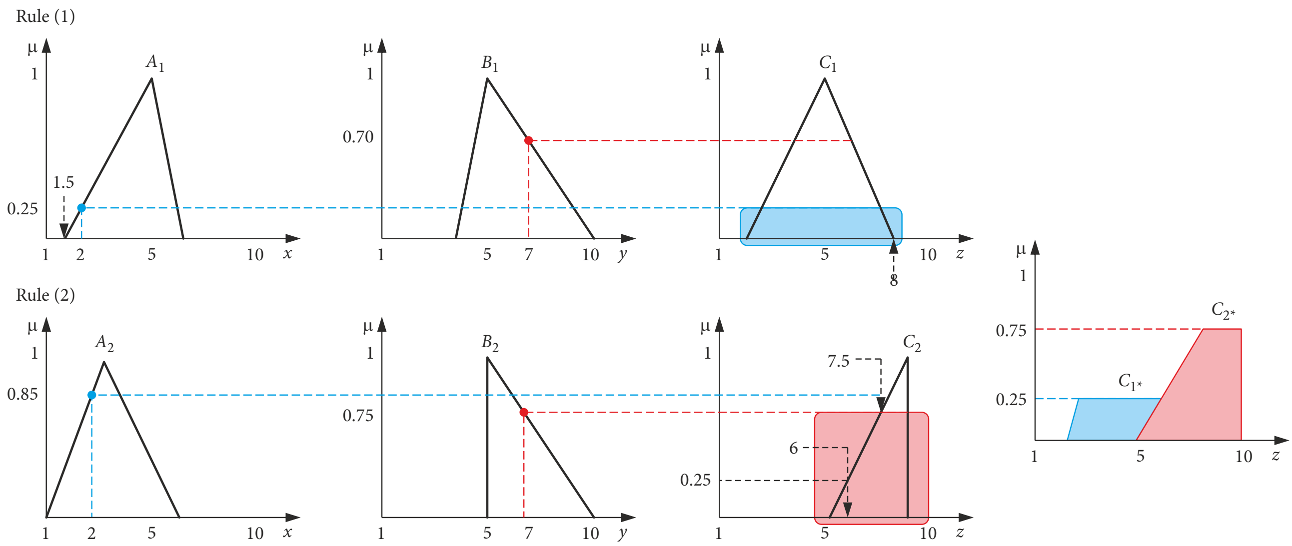

Figure 3. Example of fuzzy inference

Table 2. Fuzzy inference rules applied with EOT, overlapping, and productivity

Rule	EOT		Overlapping		Work productivity		Output
1	VH	and	VH	and	VH	then	VH
2	VH	and	VH	and	H	then	VH
…							
124	VL	and	VL	and	L	then	VL
125	VL	and	VL	and	VL	then	VL

productivity is high (H), then the output is calculated as very high. The importance of factors is assigned by fuzzy AHP (Eqns (1)–(3)) to the evaluation results (VH and H).

2.5. Resources reallocation

For resource reallocation, first, the reducible construction duration and reduction cost per day are calculated. The reducible duration means that it could be reduced duration. The reducible duration is calculated by multiplying the remaining construction duration and the maximum workload, after the maximum workload by reallocated work crews is calculated in Eqn (9). In Eqn (9), "1" is subtracted because the reducible duration is a day when the maximum workload is two times higher than the planned workload. For example, if the maximum workload per day is 3,600 m^3 – while the planned workload per day is 1,800 m^3 – and the remaining duration is 25 days, then reducible duration is calculated as 25 days. Next, the reduction cost per day (Eqn (9)) is calculated by dividing the required cost for the maximum workload by the reducible duration (Eqn (10)). For example, if the reducible duration is one day and the required cost for the maximum workload is USD 2,100, then the reduction cost per day is calculated as USD 2,100:

Reducible construction duration = [(*maximum workload*/*planned workload*) – 1] × *remaining construction duration of corresponding activity*; (9)

Reduction cost per day = *maximum cost per day*/*reducible construction duration.* (10)

This study has three objective functions for resources reallocation. The first objective is to maximize the sum of the selected activities' importance for resource reallocation. The importance of reduction cost, possibility of EOT and overlapping, and work productivity are multiplied with the evaluation value of each activity and the sum of the multiplied value is maximized ($X = \sum_{i=1}^{n}\left(a \cdot w_i + b \cdot x_i + c \cdot y_i + d \cdot z_i\right)$). The sum of the maximized value is less than or equal to 1 ($X \leq 1$). The second objective is to maximize the reduced duration to satisfy the duration reduction target. The reduced duration should be maximized by reallocating the work crew. The total duration reduction ($Y = \sum_{i=1}^{n} e_i$) is less than or equal to the reducible duration ($Y \leq$ total reducible construction duration). The third objective is to minimize the reduction cost for resource reallocation. The required cost should be minimized for reducing duration ($Z = \sum_{i=1}^{n} f_i$) and the sum of cost should be less than or equal to the available cost ($Z \leq$ available cost).

$$\text{Maximize} \quad X = \sum_{i=1}^{n}\left(a \cdot w_i + b \cdot x_i + c \cdot y_i + d \cdot z_i\right); \tag{11}$$

$$\text{Maximize} \quad Y = \sum_{i=1}^{n} e_i;$$

$$\text{Minimize} \quad Z = \sum_{i=1}^{n} f_i;$$

Subject to $a \geq 0$, $w_i \geq 0$, $b \geq 0$, $x_i \geq 0$, $c \geq 0$, $y_i \geq 0$, $d_i \geq 0$, $z_i \geq 0$, $e_i \geq 0$, $f_i \geq 0$, $X \leq 1$, $Y \leq$ *total reducible construction duration*, $Z \leq$ *available cost*,

where: X – the sum of weighting by fuzzy AHP and fuzzy inference; a – weighting of reduction cost by fuzzy AHP; b – weighting of EOT by fuzzy AHP; c – weighting of overlapping by fuzzy AHP; d – weighting of work productivity by fuzzy AHP; w_i – weighting of activity i's reduction cost by fuzzy inference; x_i – weighting of activity i's EOT by fuzzy inference; y_i – weighting of activity i's overlapping by fuzzy inference; z_i – weighting of activity i's productivity by fuzzy inference; Y – the sum of the number of activity i's reduced construction duration; e_i – the reduced construction duration of activity i; Z – the sum of cost for reducing the construction duration; f_i – the reduction cost of activity i.

3. Applicability analysis

The proposed method aims to select the high priority activities considering cost and importance of influence factors for resource reallocation to reduce per day when the construction duration is delayed. Through a case study, how the result of the method presented is explained in this section. The case project that is combined cycle power plant includes 1,280 activities and 608 CPs (Table 3).

Table 3. Time schedule of the case

Activity ID	Activity name	CP	Relationship type
1	Opening sit office	Yes	
2	EPC pre-agreement	Yes	Finish to start
…			
1279	Fire-fighting transfer pump installation	No	Finish to start
1280	Fire-fighting transfer pump test	No	Finish to start

In terms of the relationships between activities, the number of activities that have a finish to start relation is 1,328, the number of activities that have a start to start relation is 685, the number of activities that have a finish to finish relation is 95, and the number of activities that have a start to finish relation is 3. To explain the application procedure, several activities (A–J) are selected (Table 4).

First, for selecting the activities based on the cost slope, the reducible duration is calculated (Table 4). The planned workload per day by a work crew (m^3/day) and the number of work crew are multiplied and then the planned total workload (m^3/day) is calculated. The maximum number of work crew for each activity and the planned workload per day by a work crew (m^3/day) are multiplied and then the maximum total workload is calculated. The reduced duration (day) is calculated by Eqn (9) using the calculated values of planned and maximum workloads and the remaining construction duration. If the calculated reducible duration includes a decimal point, then the rounded down value is used. For calculation of reduction cost per day (Table 5), the maximum cost per day is calculated by multiplying the unit cost (USD) of each work crew by the maximum number of work crew (Table 4). Here, if the maximum number of work crew includes a decimal point, then the rounded up value is used because the work crew is composed of person. If the maximum cost per day is divided by the calculated construction duration (Table 4), then the reduction cost per day is calculated (Eqn (10)). Based on the reduction cost per day, 10 are selected (A-J activities) that are the lowest-cost activities for reducing per day using the proposed method (Figure 2).

For priority analysis of activities, the importance of influence factors, such as possibility of EOT and overlapping, and work productivity, is analyzed using fuzzy AHP. This study uses the verified triangular fuzzy number from a previous study (Table 6). The evaluation results of influence factors are calculated based on this triangular fuzzy number (Table 7). A survey was conducted during about 2 weeks (July 29 – August 11, 2019) by email. The survey was answered by a total of 34 project managers, whose experience is varied: 5 persons had 20 or more years of experience, 4 persons had 16–20 years of experience, 10 persons had 11–15 years of experience, 10 persons had 6–10 years of experience, and 5 persons had 5 or less years of experience.

The geometric averages (T_{ij}) of the triangular fuzzy number (Table 7) are applied to Eqn (1) for the importance analysis of influence factors (Table 8). When the importance of factors is represented by W_i and W_j, the possibility of $W_i \geq W_j$ and $W_j \geq W_i$ represents $P(W_i \geq W_j)$ and $P(W_j \geq W_i)$. After the possibility is applied to Eqn (2) (Table 9), the minimum value is derived as work productivity (1.00), overlapping (0.0.885), and EOT (0.627) using Eqn (3) (Figure 4). Namely, the importance of work productivity is the highest and EOT is the lowest because an uncertainty of EOT approval is high.

Table 4. The reducible construction duration

Activities	A	B	C	D	E	F	G	H	I	J
Workload of a crew (m^3/day)	150	200	170	80	110	130	210	160	225	185
Planned number of crew	11	15	10	14	16	10	9	8	9	11
Planned workload (m^3/day)	1,650	3,000	1,700	1,120	1,760	1,300	1,890	1,280	2,025	2,035
Max. number of crew	14	20	13	18	21	13	12	10	12	14
Max. workload (m^3/day)	2,145	3,900	2,210	1,456	2,288	1,690	2,457	1,664	2,633	2,646
Remaining duration (day)	21	17	15	12	16	13	11	12	15	14
Reducible duration (day)	6.3	5.1	4.5	3.6	4.8	3.9	3.3	3.6	4.5	4.2

Table 5. The required cost for duration reduction

Activities	A	B	C	D	E	F	G	H	I	J
Unit price (USD)	300	180	170	230	250	200	170	220	270	300
Max. required cost (USD)	4,500	3,600	2,210	4,370	5,250	2,600	2,040	2,420	3,240	4,500
Reduction cost per day (USD)	750	720	553	1,457	1,313	867	680	807	810	1,125

Table 6. The triangular fuzzy membership number (Pan, 2008)

Linguistic values	Triangular fuzzy numbers
Very low	(1, 1, 2)
Low	(1, 2.5, 4)
Middle	(3, 5, 7)
High	(6, 7.5, 9)
Very high	(8, 10, 10)

Table 7. The geometric average based on the fuzzy triangular number

	EOT	Overlapping	Work productivity
EOT	(1, 1, 1)	(1.86, 2.93, 4.42)	(1.70, 2.69, 4.14)
Overlapping	(3.79, 4.90, 6.46)	(1, 1, 1)	(2.40, 3.42, 4.96)
Work productivity	(4.11, 5.38, 6.83)	(2.91, 4.34, 5.85)	(1, 1, 1)

The importance of each activity is analyzed using fuzzy inference (Eqns (5)–(8)) and the result is assumed by an expert in this case study. Then the values are multiplied by the result of the fuzzy AHP for priority analysis (Table 10). The resulting order of priority is represented as (C, F), (E), (B), and (A, D, F, H, I, J). Based on the priority, resources are reallocated for reducing the construction duration target.

For resource reallocation, Eqn (11) is calculated about 39 times because the calculated reducible duration is 39 days (Table 4). First, the highest priority activity is reduced by a day. This study assumes that DLDs by delay per day are USD 10,000, that the incentive by reduction per day is USD 5,000, and that the duration of the delay is 27 days at the cut-off day. As a result (Figure 5), if the reduction duration is increased, then the economic benefit is also increased linearly because the size of the DLDs and incentives is greater than the reduction cost of duration in this case project. The slope is small when the reduced duration is 28 days because the size of DLDs is larger than of the incentives. The reduction cost is USD 680 by a day and the DLDs are USD 26,000 because of decreased USD 10,000 by reduction a day. Thus, the total required cost is USD 260,680. If 27 days are reduced, then the DLDs are 0 and the incentives are increased by USD 5,000 per reducing day from 28 days reduced. If the reduced duration is 33 days or more, then the sum of the resource reallocation costs, the DLDs, and the incentives turns loss into gain. When all reducible durations (39 days) are reduced, an economic benefit is USD 25,270.

Table 8. The importance of the triangular fuzzy number for the selection factors

EOT	Overlapping	Work productivity
(0.13, 0.25, 0.48)	(0.20, 0.35, 0.63)	(0.23, 0.40, 0.69)

Table 9. The result of $P(W_i \geq W_j)$

$P(W_i \geqq W_j)$	Value	$P(W_i \geqq W_j)$	Value	$P(W_i \geqq W_j)$	Value
$P(W_1 \geqq W_2)$	0.74	$P(W_2 \geqq W_1)$	1.00	$P(W_3 \geqq W_1)$	1.00
$P(W_1 \geqq W_3)$	0.63	$P(W_2 \geqq W_3)$	0.88	$P(W_3 \geqq W_2)$	1.00

Table 10. The importance of each activity by fuzzy inference

Activity	EOT		Overlapping		Productivity		Output	
	EV	WV	EV	WV	EV	WV	EV	WV
A	8	5.02	6	5.31	4	4.0	6	0.50
B	6	3.76	8	7.08	8	8.0	7.3	0.65
C	8	5.02	10	8.85	10	10.0	9.3	0.75
D	4	2.51	8	7.08	8	8.0	6.7	0.50
E	2	1.25	10	8.85	10	10.0	7.3	0.68
F	2	1.25	8	7.08	8	8.0	6	0.50
G	10	6.27	8	7.08	8	8.0	8.7	0.75
H	4	2.51	8	7.08	8	8.0	6.7	0.50
I	6	3.76	6	5.31	6	6.0	6	0.50
J	4	2.51	8	7.08	8	8.0	6.7	0.50

Note: EV is evaluated value by the expert and WV is weighted value by fuzzy AHP.

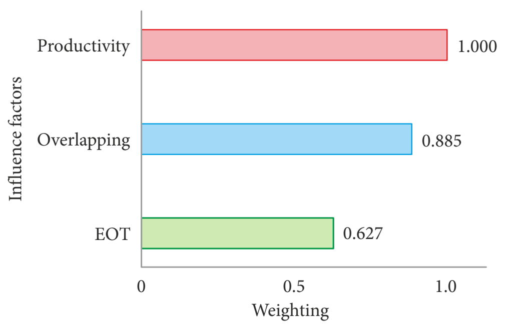

Figure 4. The importance of the selection factors by fuzzy AHP

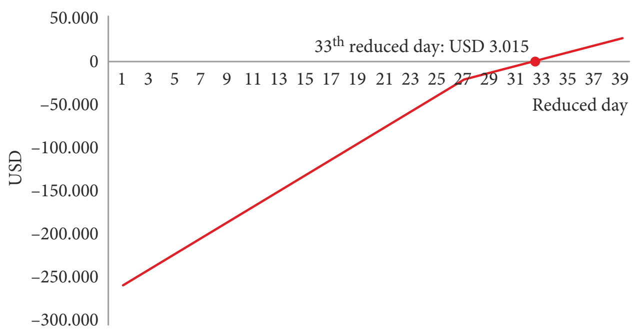

Figure 5. The economic analysis of the proposed method according to duration reduction

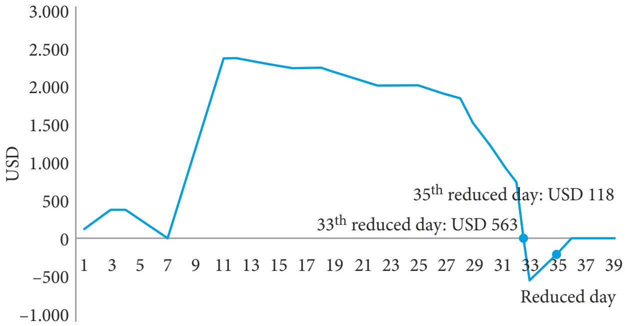

Figure 6. The comparison between the proposed and cost slope method

The results of resource reallocation by the proposed method are compared with those of the cost slope method (Figure 6). The cost slope method is based on reduction cost per day and on reducible construction duration in each activity. That is, the cost slope method utilizes cost and excludes the overlapping and work productivity included in Eqn (11). The differences between the methods are not great until 7 days are reduced but the differences increase greatly from 8 to 32 days are reduced. Thus, the resource reallocation is effective, according to the decision-maker's preferences regarding the importance of activities and the economic benefit. When 33 days or more are reduced, the economic benefit of the two methods are similar because the cost of the proposed method is small and the cost of the slope method is large, thus, if the change in the economic benefit is compared according to the reduction duration under available cost, then decision-makers can choose between the two methods according to their preferences.

4. Discussion

If the contracted construction duration is delayed, the level of duration reduction is determined by considering the increased costs for resource reallocation, delay liquidated damages (DLDs), and incentives by reducing the contracted duration. Previous studies have proposed methods to solve the time-cost trade-off problem by duration reduction (García-Nieves et al., 2019; Haj & El-Sayegh, 2015; Liu & Wang, 2011). These methods used reduction cost per day as the selection criterion for resource reallocation activities. However, the influence factors for resource reallocation exist as well as the reduction cost. And, the increases in CP and in economically feasible alternatives that result from a reduced construction duration should be considered, as thousands of activities are interrelated. This study proposed a method for selecting activities that are organically related to the reallocation of resources based on the increased construction cost and incentives and decreased DLDs. The proposed method can assist in deciding whether to reduce the construction duration when the project is delayed.

Previous studies have proposed the use of methods such as genetic algorithm (GA) to reallocate resources for duration reduction. This study, however, utilizes these methods for both priority analysis and resource reallocation. Of special note, the fuzzy AHP and fuzzy inference are proposed for analysis of the importance of an influence factor on the construction duration. These assist in decision making, as the importance of individual activities can vary between construction projects, and, generally, a project entail thousands of interrelated activities. Among the commonly-used methods for analyzing the weighting of an activity, AHP, a method that is based on expert knowledge, is especially useful when there is a shortage of information about the evaluation target. This study uses AHP and expert evaluations to analyze the importance and weighting of various influence factors of the construction duration. A notable limitation of AHP is the inconsistency of evaluation results when the evaluation factors are many or when the expertise of evaluators is widely varied. Thus, this study used fuzzy AHP to reduce language ambiguities.

The proposed method did not include management factors, as they are difficult to quantify, and assumed that quality, safety, and environment factors could be satisfied. Future study should propose methods for quantifying the various factors and for reducing the analysis time related to resource reallocation. A notable advantage of the method proposed in this study is that it reflects both the preferences of decision-makers in resource reallocation and the characteristics of each project, as various influence factors, including construction cost, are evaluated.

Conclusions

This study proposed a method for reducing the construction duration includes two steps: (1) Priority analysis based on lowest-cost activity and the importance of influence factors on resource reallocation; (2) Resources reallocation based on the priority of influence factors.

First, the combinations of the lowest-cost activities are derived, and then the influence factors are derived as the possibility of extension of time (EOT) approval, the possibility of overlapping, and work productivity based on previous studies (Ammar, 2013; Durdyev et al., 2018; FIDIC, 1999; Huang et al., 2016; Mirahadi & Zayed, 2016; Moon et al., 2015; Srour et al., 2013). The importance of factors is analyzed through an expert survey and using the fuzzy analytic hierarchy process, and the importance of each activity is also analyzed using fuzzy inference. The priority of activities is derived by multiplying the results. Next, based on the priority of activities, resources are reallocated, where objective functions are to maximize the sum of the importance of selected activities and the construction duration reduction as well as to minimize the reduction cost. Finally, the results of the economic analysis of the proposed method and the existing cost slope method are compared – and an economic benefit is presented to decision-makers quantitatively, according to changing the duration reduction. Thus, decision-makers can determine whether or not to use the methods based on the duration reduction target, economic benefit, and preferences.

A limitation of this study is that it did not include qualitative factors, such as those related to management, as factors influencing resource reallocation. A future study will propose a method for prioritizing the thousands of interrelated activities, taking qualitative as well as quantitative factors into consideration. However, if the proposed method is used, the decision-makers could determine the priority of resource reallocation based on the qualitative importance of each activity and reduction cost. The method can apply specific project characteristics and decision-maker preferences; thus, it can contribute to effective decision-making. In particular, if the reduction cost of several activities is the same, then the method can be applied usefully.

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APPENDIX

Table A1. The parameters used in this paper

Equation	Parameters
Fuzzy AHP	T_i – a triangular fuzzy membership number of activity i
	l_i – low value of T_i, m_i – middle value of T_i, h_i – high value of T_i
	W_i – an importance of activity i
	$P(W_i \geq W_j)$ – a possibility of when W_i larger than W_j
Fuzzy inference	w – the degree of compatibility
	$\mu_A(x)$ – a membership function for whether element x is included in set A
	$\mu_B(y)$ – a membership function for whether element y is included in set B
	$\mu_{Ck}(z)$ – a membership function of C_k, C_k – the output of rule
	$\mu_C(z)$ – a final output based on $\mu_{Ck}(z)$
	Z_* – a constant value based on the calculated fuzzy value
Resources reallocation	X – the sum of weighting by fuzzy AHP and fuzzy inference
	a – weighting of reduction cost by fuzzy AHP
	b – weighting of EOT by fuzzy AHP
	C – weighting of overlapping by fuzzy AHP
	D – weighting of work productivity by fuzzy AHP
	w_i – weighting of activity i's reduction cost by fuzzy inference
	x_i – weighting of activity i's EOT by fuzzy inference
	y_i – weighting of activity i's overlapping by fuzzy inference
	z_i – weighting of activity i's productivity by fuzzy inference
	Y – the sum of the number of activity i's reduced construction duration
	e_i – the reduced construction duration of activity i
	Z – the sum of cost for reducing the construction duration
	f_i – the reduction cost of activity i