Developing a Process Model for Optimizing Linear Process Plans Based on Three Types of Buffers and Brute-Force Algorithm

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Abstract

The network and the bar chart scheduling method have been widely used so far without distinguishing non-repetitive and repetitive construction projects. However, these scheduling methods have limitations when it comes to establishing effective process plans for construction projects in which construction crews with different levels of productivity carry out repetitive activities by shifting their locations in serial order. Thus, in construction projects with many repetitive processes, the linear scheduling method (LSM) would be more appropriate for establishing effective process plans because it visually expresses the crew productivity for each activity in a unit space. In the case of LSM, however, since the relationship between activities is not clear and its establishment also has limitations, the optimization on LSM in terms of the construction cost or time is a very limited and subjective matter, even for scheduling experts. Therefore, the objective of this research is to develop a process model based on Brute-Force Algorithm for optimizing linear process plans, in consideration of the correlation between the construction cost and time, by utilizing the three types of buffers. These buffers are developed to establish the relations between activities both quantitatively and logically by considering the characteristics of LSM.

Keywords: repetitive process; linear scheduling method; process model; optimization; 3 types of buffers; brute-force algorithm

1. Introduction

1.1 Research Background and Objective

It is difficult to find experts with professional knowledge of various scheduling techniques in the diverse areas of the construction industry.

Due to this shortage of experts in the scheduling of construction projects, network construction schedules such as the critical path method or the bar chart that can be easily handled even by non-experts have mainly been used so far. However, these have lacked classification of non-repetitive activities and repetitive activities types and have had no particular improvement for half a century (Choi 2009).

In the projects composed of repetitive activities out of various activity types, however, the use of the network scheduling technique and the bar chart lacks consideration of activity repetitiveness and space-based productivity, and it is difficult to identify the interference between different types of activities in advance and take action since the construction schedule is prepared with the network based on unit activities.

Thus, in a project that is mainly composed of repetitive activities, the linear scheduling technique (hereafter LSM), which can represent visually and simply the mutual relationship for each space between repetitive activities on the basis of the linear graph theory, rather than network-based planning and scheduling, is considered to be much more efficient than the network scheduling technique or the bar chart.

However, since LSM lacks factors that clarify the mutual connections between activities, like the relationship of network scheduling technique, its reflection of the relationship between activities is not clear, and it has the disadvantage of low utilization because no method has been developed for calculating the construction time and cost systematically, with connection to planning and scheduling in the construction planning stage. For this reason, network-based planning and scheduling has been used so far, which has an emphasis on construction cost and time and advantages in their time analysis for planning and scheduling of construction projects (Ryu 2011).

Thus, in this research, efforts are made to develop a process model that is optimized for Linear Planning.
and Scheduling based on Brute-Force Algorithm, to establish optimized linear planning and scheduling in consideration of the correlation between the construction cost and time by developing and utilizing 3 types of buffers to reflect on LSM the characteristics of the concept of establishing the relation between activities in the network scheduling technique, and then to establish both quantitatively and logically a new relation between activities.

1.2 Research Scope and Method

In order to accomplish the research objective, the method of establishing the relationship between activities in LSM, such as the relationship of the network scheduling technique, should be newly established and utilized. Thus, the scope of this research is to develop a new method for establishing the relations between activities in LSM, as described above, to calculate and analyze the optimized construction cost and time by utilizing the optimal time-cost trade analysis technique, and to develop a process model for optimizing linear planning for determining an optimized construction schedule depending on the objective of use. At this time, planning and scheduling that is optimized in full consideration of construction site situations can be achieved by limiting the construction deadline desired by construction site managers and the number of equipment fed to each activity in accordance with site conditions.

The procedures and methods used to carry out this research can be summarized as shown in Fig.1.

2. Consideration of Existing Research

2.1 Linear Scheduling Method

The linear scheduling technique (LSM) can also be called the Vertical Production Method, Time-Space Scheduling Technique, or Repetitive-Unit Construction.

The basic form of linear planning and scheduling is shown in Fig.2., in which the vertical axis means the work space and the horizontal axis the construction date (time); Architectural structures are expressed by the floor and roads by the section or distance. The slope of solid lines represents the planned productivity of each activity. Since the relationship between repetitive activities occurring on the same work space with a certain time-buffer is simply illustrated with the individual linear solid line of each activity, the LSM is valuable for scheduling construction projects that include repetitive activities.

The network scheduling method has the advantages of clear mutual connection between activities, ease of understanding the critical path, and the possibility of establishing optimized planning and scheduling with the help of computers, but it also has a disadvantage of being unsuitable for repetitive activities due to a very low level of visual understanding.

Thus, for repetitive activities, the linear scheduling technique is found to be more efficient than the network scheduling technique. But while linear planning and scheduling was introduced to the industry a long time ago, very little related research has been done, except on a type of TACT scheduling method (Ryu 2010).

Though the domestic research is not sufficient, foreign research is more active.

Johnson (1981) was the first to propose the concept of LSM, presenting through a survey to constructors that the problems generated by the existing bar Chart and CPM could be resolved by using the LSM method. Since the 1990s, optimization studies have been done to use LSM more efficiently.

Mattila and Abraham (1998) studied the problem of resource distribution, which is handled a great deal by the linear scheduling and other scheduling techniques.

In addition, Damci (2013) developed a model for an LSM process plan by using Multi-Resource Leveling, and Tang (2014) developed a model for two-step optimization of resource distribution to reduce construction time.

However, most of these international research activities on optimization problems have focused on resource allocation and distribution. Little research has been done to optimize the existing rationally planned planning and scheduling in consideration of the correlation between the construction cost and the project time, and to present new optimized planning and scheduling.

2.2 Optimization Research on Network Scheduling Method

In the area of the network scheduling technique, a number of studies on planning and scheduling optimization have been conducted to improve the
productivity of construction projects and efficiently utilize resources.

TCTA (Time-Cost Tradeoff Analysis) model, the technology for efficient planning and management of schedules based on the optimal relation between the construction time and the construction cost was investigated in detail.

In construction projects there is a trade-off relationship between total construction cost and construction time. If the mobilization of equipment and resources is increased to reduce the construction time, the construction cost increases. On the other hand, if the mobilization is reduced to cut down the construction cost, the construction time increases.

Attempts are made to establish an optimization model for linear planning and scheduling by utilizing the construction cost/time correlation as shown above, and the method of establishing alternatives to work inputs for each activity and then selecting the best alternative to fit the relevant objective for each activity. 

2.3 Application of Predecessor/Successor-Activity Relationship of Linear Planning and Scheduling

In order to establish the optimization model for linear planning and scheduling, the TCTA optimization model of the network scheduling technique is utilized.

However, in order to optimize the linear process plan, the concept of the relationship of the network scheduling technique should also be established first in the linear scheduling method.

Thus, in order to find, in the linear planning and scheduling, the meaning of the relationship which expresses the inter-activity relation of the network scheduling technique, each factor of the linear planning and scheduling was investigated as shown in Fig.3.

As investigated in Fig.3, though the cases of divergence, convergence, and interference are three factors to show the form of slopes for representation of the productivity for each predecessor/successor activity, the case of buffer means the floating time to limit the interference of the slope between predecessor and successor activities.

The concept of buffer, which means the floating time between predecessor and successor activities out of the various factors of linear planning and scheduling, was considered as an alternative to establish in LSM the relation between activities, just like the relationship of the network scheduling technique.


The developed optimization process model may be utilized to develop an optimized schedule based upon the schedule planned rationally in its own way prior to construction project execution in consideration of the correlation between the construction cost and the construction time.

The process model that is optimized for linear planning and scheduling is illustrated in Fig.4. The detailed explanation for each process of the process model is as follows.

3.1 Preparation of Activity List Based on Existing Process Plan

The first step in the optimization process model for linear plans is the process of determining the information required for optimization by analyzing the activities planned rationally prior to project execution before the optimization of linear planning and scheduling is established. The process is as follows. Prepare the activity list for each location required for optimization from the construction plan and detailed statement of the existing process planned rationally. In addition, determine the work quantity allocated to each activity, and analyze the information on the construction work crew (equipment, labor, etc.) to handle the work quantity.

3.2 Establishment of Activity and Information for Optimization

Establish alternatives by using the work quantity and construction work crew (equipment, labor, etc.) of the activities for each location, and then calculate the direct construction cost and construction time (duration) of the alternatives of each activity (meaning that each activity may have many alternatives).

In addition, establish, for the execution of optimization, the relation between the predecessor and successor activities by utilizing the developed 3 types of buffers. The details of each process are as follows:

3.2.1 Establishment of Alternatives to Activities for Each Location

Linear planning and scheduling should be classified into the activities for each location, and alternatives should be established for each activity. Each alternative means the factors to affect the construction time (duration) of the relevant activity.

As an example, in cases in which the construction equipment is fed to the relevant activity, alternatives are established by changing the capacity and number of the construction equipment. When labor is fed into work, alternatives are established by changing the number of labors fed in.

However, when alternatives are established without limiting the construction work crew (equipment + labor) procurable on sites, unrealistic planning and scheduling can result. Therefore, construction site managers should establish alternatives by limiting the number of equipment available for each activity in
In the process of optimization, in order to exclude any alternative that exceeds the amount of equipment limited by construction site managers, out of the various established alternatives, Y value, as shown in No. 1 of Fig. 5., is assigned to each alternative. When the alternative exceeds the limited number of equipment, a large number like 1,000,000 is designated as the Y value. If not, 1 is designated as Y value for the alternative.

Y value is multiplied by the direct cost of each alternative, and so the final direct cost of the alternative to which a big number is assigned has a big value. The alternative with such a big value is not selected during optimization since it is not in agreement with the objective of this research (minimum construction cost).

3.2.2 Calculation of Construction Cost and Construction Time for Established Alternatives

First of all, the construction duration \( D_{ij} \) of each alternative is calculated. The construction duration \( D_{ij} \) is calculated using the quantity information \( Q_{ij} \) of each activity and the productivity \( P_{ij} \) of each alternative construction work crew (construction equipment, labor) deduced from the prepared detailed statement prior to the construction (see Equation 1).

\[
D_{ij} = \frac{Q_{ij}}{P_{ij}} \quad \text{Equation (1)}
\]

Next, the indirect construction cost \( DC_{ij} \) of each alternative is calculated, which means the cost generated in the case of using construction equipment and labor for the total work hours (daily work hour 8 hours \( \times \) \( D_{ij} \)).

The formula for calculation of the direct construction cost for each alternative is expressed by equation (2), which utilizes Y value to judge whether or not the total work hours, the cost generated by feeding of construction work crew, and the limited number of equipment are exceeded.

The cost generated by feeding in the construction work crew means hourly expense + labor cost + material cost. If the established alternative is a piece of construction equipment, the construction cost is calculated by using the equipment cost and hourly rent fee coefficient due to the construction equipment of the relevant alternative. For labor, the direct construction cost is calculated by utilizing the unit cost of labor and the labor input due to the labor fed to each activity type (see Equation 2).

\[
DC_{ij} = 8 \times D_{ij} \times (EC_{ij} + LC_{ij} + MC_{ij}) \times Y \\
\text{……………………………… Equation (2)}
\]

i: Number of Activity, \( i = \{A, B, C, \ldots \ldots \} \)

j: Alternative of Activity, \( j = \{1, 2, 3 \ldots \ldots \} \)

\( DC_{ij} \): Direct Cost for Alternative \( j \) of Activity \( i \)

\( EC_{ij} \): Expense for Alternative \( j \) of Activity \( i \)

\( LC_{ij} \): Labor Cost for Alternative \( j \) of Activity \( i \)

\( MC_{ij} \): Material Cost for Alternative \( j \) of Activity \( i \)

3.2.3 Establishment of Inter-Activity and Intra-Activity Relations

In order to calculate the start time and finish time of each alternative, the inter-activity and intra-
activity relations are established. It is only possible to establish an optimized process plan which enables a comparative analysis with the existing process plan if the established relation for each activity of the existing process, planned rationally, is first applied to the optimization model.

Thus, prior to the execution of optimization, the predecessor/successor relation of each activity is established, and the start time and finish time of each alternative are calculated.

In the case of CPM, the relation between activities is established by using FS, FF, SF and SS. Since this research focuses on the optimization of Linear Planning and Scheduling, however, the relation between activities was established by using buffer, which means the floating time between predecessor and successor activities.

In this research, the existing time buffer was utilized by classifying it into 4 types (FSTB, FFB, SSTB, SFTB), and the existing space buffer was also utilized by classifying it into 4 types (FSSB, FFSB, SSSB, SFSB).

In addition to the two buffers, other buffers were utilized within activities to establish not only the relation between activities but also the relation generated due to space move within the same activity. This enabled the establishment of the floating time and limitation of the interference.

First, establishing the relation in consideration of the time buffer and having the same meaning as the existing time buffer, this is the buffer with the relationship between the predecessor and successor activities within the same space. The existing buffer was divided into 4 types, and then established as shown in Fig.6.

![Fig.6. Time Buffer](image)

① FSTB (Finish-Start Time Buffer): The relation between the finish time of the predecessor activity and the start time of the successor activity is interpreted as the same meaning as FS of CPM. ② FFTB (Finish-Finish Time Buffer): The relation between the finish time of the predecessor activity and the finish time of the successor activity is interpreted as the same meaning as FF of CPM. ③ SSTB (Start-Start Time Buffer): The relation between the start time of the predecessor activity and the start time of the successor activity is interpreted as the same meaning as SS of CPM. ④ SFTB (Start-Finish Time Buffer): The relation between the start time of the predecessor activity and the finish time of the successor activity is interpreted as the same meaning as SF of CPM.

Second, establishing the relation in consideration of the space buffer and having the same meaning as the existing space buffer, this is the buffer with the relationship between the predecessor and successor activities in different spaces. As shown in Fig.7., the existing buffer was divided into 4 types and then established.

① FSSB (Finish-Start Space Buffer): FSTB establishes the FS relation between the predecessor and successor activities in the same space, but FSSB establishes the FS relation between the predecessor and successor activities in different spaces. ② FFSB (Finish-Finish Space Buffer): FFTB establishes the FF relation between the predecessor and successor activities in the same space, but FFSB establishes the FF relation between the predecessor and successor activities in different spaces. ③ SSSB (Start-Start Space Buffer): SSTB establishes the SS relation between the predecessor and successor activities in the same space, but SSSB establishes the SS relation between the predecessor and successor activities in different spaces. ④ SFSB (Start-Finish Space Buffer): SFTB establishes the SF relation between the predecessor and successor activities in the same space, but SFSB establishes the SF relation between the predecessor and successor activities in different spaces.

Third, in addition to the establishment of the relation between activities, the relation is also established within an activity of the same nature along the move of space by establishing the buffer within an activity.

By utilizing 3 types of buffers as mentioned above, the relations between predecessor and successor activities and the floating time are established. Where both the time buffer and the space buffer exist, however, they are limited by selecting the bigger value out of the buffer values between the predecessor and successor activities.
3.2.4 Calculation of Schedule for All Alternatives of Each Activity
The ST and FT of each alternative are decided by the relation establishment and construction time of the existing process plan. Depending on which alternative is selected from the construction work crew alternatives of each activity, the final construction time of the relevant activity is decided, and then the ST and FT are decided on the basis of the construction time.

3.3 Execution of Optimization with the Objective of Minimum Construction Cost
For the execution of optimization (targeting the minimum construction cost), the objective function and constraints are established. During this process, the optimal path is found by utilizing Brute Force Algorithm out of the problem of minimum cost flow.

Brute Force Algorithm is the algorithm used to deduce the path suitable to the objective from the calculated distances (cost in this research) of all the paths from one peak to another.

The problem of optimization for establishment of the linear planning and scheduling with a minimum construction cost is defined as expressed by the following equation (3).

\[
\text{Min} \left( \sum_{i=1}^{n} \sum_{j=1}^{m} (DC_{ij} \times X_{ij}) + (IDC_{D} \times D_{T}) \right) \\
\text{s.t.} \quad D_{T} \leq D_{w} \\
\sum_{i=1}^{n} \sum_{j=1}^{m} X_{ij} = 1 \\
X = \{0,1\}
\]

In the objective function, \( \sum_{i=1}^{n} \sum_{j=1}^{m} (DC_{ij} \times X_{ij}) \) means the total direct cost, and \( X_{ij} \) the conditional equation to decide whether or not the established alternatives are selected. \( IDC_{D} \times D_{T} \) means the total indirect cost, IDC, the daily indirect cost, and D_T the total construction time.

There exist two constraints. The first constraint is the conditional equation to limit the total construction time, which is defined to determine scenarios available within the construction time (D_w) desired by construction site managers.

The second constraint is the conditional equation to select alternatives suitable to the objective function. The equation is defined to have 0 or 1 as the condition for selection or non-selection.

3.4 Establishment of Optimum Process Plan Based on Optimum Process Scenarios
The optimum linear planning and scheduling is established by utilizing the process scenarios selected by the above process. First of all, by utilizing the construction time and start/finish time of the alternatives selected for each activity, the slope (G) of each activity is calculated to prepare the linear construction schedule (see Equation 4).

\[
G = SN + \left( \frac{(Day_{g} - ST + 1)}{(D_{ij} - 1)} \right)\\n\]

In equation (4), SN is the space number assigned by each activity, the data to represent the slope of the relevant activity in the relevant space. Day means the construction date of the alternatives selected for the relevant activity, and ST the start time of the relevant activity.

After calculating all of the dates and all of the slope values of each activity using the above equations, the construction schedule is deduced. In addition, the construction time and cost of the selected path are calculated.

A comparative analysis with the existing process plan is performed by utilizing the calculated construction time/cost and the linear construction schedule so that construction site managers may establish an efficient process plan.

4. Case Study
4.1 Verification through Case (1)
Case (1) is a new construction of Hall B, Exposition A, in which the total construction time is 483 days, and the total construction cost is 27 billion and 55 million won. Fig.8. below shows the linear construction schedule already planned.

Optimization is performed by establishing the alternatives of the activities with slow slopes and then establishing the predecessor/successor activity relation with buffers. Out of a total of 59 activities, the number of activities with a buffer value of 0 is 35 and the number of activities with a buffer value of 1 or more is 24. Table 1. shows the buffer value of activities with the buffer value of 1 or more.

As a result, a linear construction schedule like the one shown in Fig.9. was deduced: The total construction cost is 26 billion and 950 million won and the total construction time 392 days. Table 2. shows the analysis results for comparison in the construction cost and time between the existing process plan and the optimum process plan.

![Fig.8. Existing Process Schedule (Case (1))](image)
The total construction cost was decreased by 3.8%, from 27 billion and 550 million won to 26.5 billion won. Finally, the construction time was decreased by 19%, from 483 days to 392 days. The results above show the lowest construction cost on the path with the construction time below 400 days, which was limited during the process of optimization.

4.2 Verification through Case (2)

Case (2) is a new construction of Apartment B, in which the total construction time is 954 days, and the total construction cost is 41 billion and 500 million won. The buffer setting value of this case was used by deducing the inter-activity and intra-activity floating times from the real construction log of this case. Optimization is performed by establishing the alternatives of the activities with gentle slopes and establishing the predecessor/successor relation of each activity with buffers. Out of a total of 148 activities, the number of activities with a buffer value of 0 is 116 and the number of activities with a buffer value of 1 or more is 32. Table 3. shows the buffer value of activities with the buffer value of 1 or more. Fig.10. shows the existing linear construction schedule.

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**Table 1. Buffer Setting Values of Case (1)**

<table>
<thead>
<tr>
<th>Activity Number</th>
<th>Activity Name</th>
<th>Successor Number</th>
<th>Successor Name</th>
<th>Buffer</th>
</tr>
</thead>
<tbody>
<tr>
<td>B01</td>
<td>Pile</td>
<td>C01</td>
<td>Cutting work</td>
<td>FSTB</td>
</tr>
<tr>
<td>R07</td>
<td>Roofing</td>
<td>M02</td>
<td>Interior</td>
<td>FSSB</td>
</tr>
<tr>
<td>K05</td>
<td>Windows Work</td>
<td>K06</td>
<td>Windows Work</td>
<td>AB</td>
</tr>
</tbody>
</table>

**Table 2. Case (1) Comparative Analysis between Results of Existing and Optimum Process Plans**

<table>
<thead>
<tr>
<th>Item</th>
<th>Existing Process Plan</th>
<th>Optimum Process Plan</th>
<th>Rate of Increase/Decrease</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Construction Cost (Entire Items)</td>
<td>27 billion and 550 million won</td>
<td>26.5 billion won</td>
<td>3.8% Decrease</td>
</tr>
<tr>
<td>Construction Time</td>
<td>483 days</td>
<td>392 days</td>
<td>19% Decrease</td>
</tr>
</tbody>
</table>

The total construction cost was decreased by 3.8%, from 27 billion and 550 million won to 26.5 billion won. Finally, the construction time was decreased by 19%, from 483 days to 392 days. The results above show the lowest construction cost on the path with the construction time below 400 days, which was limited during the process of optimization.

**Table 3. Buffer Setting Value of Case (2)**

<table>
<thead>
<tr>
<th>Activity Number</th>
<th>Activity Name</th>
<th>Successor Name</th>
<th>Buffer</th>
</tr>
</thead>
<tbody>
<tr>
<td>A01</td>
<td>Excavation</td>
<td>B01</td>
<td>FSTB</td>
</tr>
<tr>
<td>B20</td>
<td>Structural Work</td>
<td>E01</td>
<td>FSSB</td>
</tr>
<tr>
<td>H17</td>
<td>Masonry Work</td>
<td>H18</td>
<td>Masonry Work</td>
</tr>
<tr>
<td>H20</td>
<td>Masonry Work</td>
<td>H21</td>
<td>Masonry Work</td>
</tr>
</tbody>
</table>

**Fig.11. Optimal Process Schedule (Case (2))**
The objective function and constraints are established to perform the optimization. The objective function is searched toward the path with a low total construction cost. In this case, unlike case (1), the total construction time was not limited. As a result, a linear construction schedule like Fig.11. was deduced. The total construction cost is 38 billion and 480 million won and the total construction time 815 days. Table 4. shows the analysis results for comparison in the construction cost and time between the existing process plan and the optimum process plan. The total construction cost was decreased by 8%, from 41.5 billion won to 38 billion and 480 million won.

5. Conclusions
In this research, attempts were made to newly develop the concept of the relationship of the network scheduling method in the linear scheduling method, for which optimization research has not been sufficient due to the difficulties in establishing the relationship between the predecessor and successor activities. Accordingly, three types of buffers were developed to quantitatively and logically establish new relations between activities by reflecting the characteristics of buffers among the various factors of the linear scheduling method.

The buffer of the existing linear scheduling method was divided into 3 types, and each type was also divided to establish the predecessor/successor relationship of the linear scheduling method in consideration of time and space conditions as follows: Time Buffer (FSTB, FFTB, SFTB, and SSTB), Space Buffer (FSSB, FFSB, SFSB, and SSSB), and Activity Buffer (AB).

On this basis, the optimum linear process plan was established by developing the optimization process model for linear process plans, which is the process of information deduction (optimum schedule, construction time, and total construction cost) which helps on-site managers make decisions. In addition, the effectiveness and validity of the optimization process model proposed in this research for linear process plans were verified through the verification of cases. The two-case results of comparative analysis between the existing process plan and the optimum process plan deduced from optimization confirmed that in case (1), the total construction cost and the construction time decreased by 3.8% and 19%, respectively, and in case (2), the total construction cost and the construction time decreased by 8% and 15%, respectively.

In addition to calculation of the construction cost and time, the advantages of the linear scheduling method were maximized through visualization of the linear schedule.

In conclusion, through this research, site managers were able to express the entire relationship of each work in LSM by utilizing 3 types of buffers developed for optimization of the linear scheduling method. Thus, it is expected that the optimization research, which has not progressed greatly due to difficulties in establishing the existing predecessor/successor activity relationship, will be conducted more actively.

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