Two-Stage Scheduling Model for Resource Leveling of Linear Projects

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Abstract: In recent times, linear project resource leveling based on the linear scheduling method (LSM) has attracted considerable interest owing to the unique advantages of applying the LSM to linear projects. In the research reported in this paper, the linear project resource leveling problem was described as a constraint satisfaction problem based on analyses conducted in previous studies and a two-stage scheduling model for resource leveling of linear projects based on the LSM was proposed. The optimization process was reasonably set so as to fully utilize the rate float of the activity to obtain a more optimal schedule. The constraint programming (CP) technique was used for solving this problem. Based on the proposed scheduling model and algorithm, a two-stage scheduling system for resource leveling of linear projects was developed for automatically establishing a linear schedule for resource leveling. The effectiveness of the proposed model and algorithm was verified for a highway construction project reported previously. **DOI: [10.1061/(ASCE)CO.1943-7862.0000862](https://doi.org/10.1061/(ASCE)CO.1943-7862.0000862).** © *2014 American Society of Civil Engineers.*

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Introduction

Network scheduling methods are widely used in the field of construction (Schwindt 2005; Mubarak 2010; Galloway 2006; Lancaster and Ozbayrak 2007). However, these traditional scheduling methods are not suitable for linear projects, such as highways, railways, pipelines, and tunnels, which are characterized by a series of successive and repetitive activities. In recent years, novel linear scheduling methods (LSMs) that afford advantages such as maintaining continuity of resources, conciseness, and vividness have been applied to linear project scheduling (Johnston 1981; Harris and Ioannou 1998; Yamín and Harmelink 2001; Reda 1990; Harmelink 2001).

Typical construction resources include manpower, machinery, materials, money, information, and management decisions (Halpin and Woodhead 1998). These resources need to be well-managed to ensure that the construction project is completed on schedule and within budget. To some extent, construction project management involves nothing but management of resources (Park 2005).

Resource management typically includes resource allocation and resource leveling. Thus far, the most important challenge was to achieve resource leveling for a construction project with fixed duration (Georgy 2008; Son and Skibniewski 1999). Resource leveling should make the demand curve of resources as smooth as possible to avoid short-term peaks or low ebbs, reduce resource and management cost, and avoid unnecessary losses.

In the research reported in this paper, optimization of linear project resource leveling based on LSM was investigated under the constraint of fixed duration. A two-stage scheduling model for linear project resource leveling was developed and it was solved using constraint programming (CP) techniques. Based on the proposed model and algorithm, a two-stage scheduling system for linear project resource leveling was developed for automatically establishing a linear schedule based on resource leveling. The proposed model and algorithm were verified by using an example of a highway construction project (Mattila and Abraham 1998; Georgy 2008).

Literature Review

Linear Scheduling Method

The LSM is directly related to the line of balance (LOB) scheduling method developed by the U.S. Navy in the early 1950s. However, the exact origin of the LSM remains unclear (Johnston 1981; Georgy 2008).

A LSM is used to describe the construction schedule of a linear project in a rectangular coordinate based on the construction characteristics of a linear project. Usually, the horizontal and vertical axes represent the spatial position and time schedule of a project, respectively. An activity can be expressed using specific symbols in a two-dimensional coordinate system in accordance with time and spatial location of construction. A two-dimensional coordinate system and its elements, both of which are used for describing the project schedule, together constitute the LSM diagram. The LSM includes key elements such as activities, rate of activities, and buffer between activities.

Linear project activities are divided into three types in accordance with the LSM, as follows: (1) linear, (2) block, and (3) bar. A linear-type activity can be divided into a full-span and partial-span linear activity in accordance with the spatial location of the activity (Harmelink and Rowings 1998). In a linear-type activity, the concept of rate indicates the spatial progress of the linear

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activity in unit time; it is the main characteristic of a linear-type activity, and it serves as an important distinction between the LSM and critical path method (CPM). In a linear scheduling diagram, the rate indicates the slope of a linear-type activity. The rate volume of a linear-type activity is indicative of and varies in proportion to the resource usage of the activity. In a linear scheduling diagram, the slope of a linear-type activity varies in proportion to the resource usage of the activity.

In a linear scheduling diagram, the distance between two activities in the horizontal and vertical directions is respectively called the distance and time buffer (Harmelink 2001; Mubarak 2010). The buffer depends on technical, managerial, or other external constraint requirements. The minimum (maximum) time and minimum (maximum) distance between two activities is called the minimum (maximum) time buffer and minimum (maximum) distance buffer, respectively.

The critical path can be calculated using schedules established by the network scheduling method. Similarly, the controlling activity path (CAP) can be calculated using schedules established by the LSM. Many studies have focused on calculation of the CAP of the LSM (Harris and Ioannou 1998; Harmelink and Rowings 1998; Kallantzis and Lambropoulos 2004; Kallantzis et al. 2007; Ammar and Elbeltagi 2001).

For a schedule established by the network scheduling method after determining the critical path, the float of activities exists on the noncritical path. Similarly, for a schedule established by the LSM after determining the CAP, the float of noncontrolling activities or noncontrolling segments of activities, called the rate float, also exists (Harmelink 2001; Mattila and Abraham 1998).

The rate float specifies the amount of possible changes in the production rate for a noncontrolling linear activity before it becomes a controlling activity (Harmelink 1995). The rate float could also be defined as "the difference between the planned production rate of an activity and the lowest possible production rate without interfering in the buffer" (Mattila and Abraham 1998).

For scheduling determined-rate activities, the existence of the rate float gives noncontrolling activities or noncontrolling segments of activities a certain degree of flexibility. Managers can then further adjust resource allocation to these parts of activities to further optimize the overall schedule.

Resource Leveling of Linear Schedule

In recent years, some studies have focused on the problem of resource leveling based on the LSM. Mattila and Abraham (1998) used an integer programming method for modeling and solving this problem. However, their study on resource leveling of linear schedules has some limitations. This process is based on an existing schedule and there is no guarantee that choosing a different initial schedule will not lead to a far better final schedule. However, this limitation was included in their method to avoid combinatorial problems. Only adjustments for resources in the noncontrolling segments of linear activities were considered in the optimization process based on CAP, which was not sufficiently flexible (Georgy 2008). Continuity between the noncontrolling and controlling segments of the same activities could not be guaranteed in the model for an optimization process based on CAP. Adjustments for the optimization process may result in discontinuity of the linear activity resource usage, thus eliminating the natural advantages of the LSM. The buffer between the activities was fixed; this in turn reduced the flexibility of the model and affected the quality of schedules. All feasible construction schedules were not considered in the optimization frame established by the researchers, such as two sets of construction schedules at

days 3 and 5 initiation of activity A and two sets of construction schedules at the days 31 and 32 completion of activity H, which further affects the quality of the solution. In summary, the greatest flaws of the model are that its optimization process focuses on a fixed schedule, noncontrolling segments of activities, and parts of feasible construction schedules; doing so cannot serve the original appearance of the problems that will be solved, and greatly affects the feasibility of the model and quality of the solution. However, to avoid combinatorial explosion (Georgy 2008) and reduce the labor and time required to construct complex models and formulas, owing to the selected mathematical methods (Heipcke 1999; Liu and Wang 2012), Georgy (2008) had to select this method to reduce the complexity of the problem.

Georgy (2008) further studied resource leveling for linear projects. In the model of Georgy (2008), an activity was considered in its entirety for resource adjustments. The limitation of the controlling path was eliminated in the optimization process and the concept of changing buffer was introduced to realize high flexibility. Simultaneously, a genetic algorithm was used for solving the model. The possibility of obtaining optimal solutions could be improved because solving was based on many initial feasible solutions. However, this approach still has some limitations. The schedule quality of the genetic-algorithm-based model could not be guaranteed owing to the characteristics of the genetic algorithm (Russell and Norvig 2009). Although the concept of changing buffer was introduced in this model subject to the efficiency of the random method for obtaining initial feasible solutions, the constraint of maximum buffer should be introduced in this model to narrow down the range of values of the buffer when there is no constraint on the maximum buffer between activities. However, this constraint-increasing and range-reducing method reduced the flexibility of the model and quality of the solution.

Only one-stage optimization was carried out in previous studies (Mattila and Abraham 1998; Georgy 2008). In Mattila and Abraham (1998), the noncontrolling segments of activities of a determined initial schedule were optimized based on the CAP; in Georgy (2008), the entire activity was optimized. Georgy (2008) discussed the results for the case in which only one-stage optimization is carried out. Mattila and Abraham (1998), which had a fixed CAP, did not allow changes to the rate of progress for the controlling portions of linear activities. In contrast, Georgy (2008) could optimize both the noncontrolling and controlling parts of the activity. Therefore, optimization of the overall activity has high flexibility and better solutions can be obtained. In the research reported in this paper, the advantages and disadvantages of a one-stage optimization process were analyzed. Accordingly, a two-stage optimization model was proposed to fully utilize the rate float of the activity to obtain a more optimal schedule.

Resource leveling of construction projects is a combinatorial optimization problem. In addition to mathematical methods and heuristic algorithms, CP is a new approach that has been applied to this problem (Pinedo 2008; Brailsford et al. 1999; Jain and Grossmann 2001; Chan and Hu 2002). Liu and Wang (2007) applied CP to resource allocation optimization of linear projects such as bridge engineering.

In the research reported in this paper, LSM was combined with CP to establish a constraint satisfaction problem (CSP)-based two-stage scheduling model for linear project resource leveling. A two-stage scheduling system for linear project resource leveling was researched and developed. The validity of the proposed model and algorithm were verified using this system.

Constraint Programming

Constraint programming is a programming paradigm that is used for solving CSPs and combinatorial problems through a combination of mathematics, artificial intelligence, and operations research techniques (Chan and Hu 2002; Liu and Wang 2012). Constraint programming implementation for combinatorial problems has the following advantages (Brailsford et al. 1999; Liu and Wang 2007, 2008): (1) efficient solution searching mechanism, (2) convenient model formulation, and (3) flexible constraint types.

To improve the computational efficiency of solving problems, CP provides users with different consistency techniques such as node, arc, and path consistency for variable domain reduction. Compared with node consistency, arc consistency has higher effectiveness in finding inconsistencies and domain reduction; compared with path consistency, arc consistency requires less constraint propagation, indicating that arc consistency processing at each node could be less expensive (Russell and Norvig 2009; Heipcke 1999; Apt 2003). Constraint programming provides different search strategies such as generate and test (GT), backtracking (BT), and forward checking (FC; Liu and Wang 2008; Marriott and Stucky 1998; Apt 2003). Selecting appropriate variables and values through heuristics should reduce the computational effort required and improve the search ability (Liu and Wang 2007; Russell and Norvig 2009; Apt 2003).

When solving an optimization problem, the objective function in the problem is treated as a constraint and this additional constraint forces the new feasible schedule to have a better objective value than the current schedule. The upper or lower bounds of the constraint are replaced as soon as a better objective function value is found. The propagation mechanism narrows the domains of decision variables to reduce the size of the search space while recording the current best schedule. The search terminates when no feasible schedule is found and the last feasible schedule is the optimal schedule (Pinedo 2008; Liu and Wang 2008).

Several approaches have been used for handling CSP-type resource-leveling problems, such as mathematical and heuristic methods including genetic algorithms and ant colony optimization (Georgy 2008; Hegazy 1999; Christodoulou 2005; Kolisch and Hartmann 2006). Mathematical methods can identify specific schedules, but their problem-solving stage usually requires much time and effort. Heuristic methods can obtain schedules in a short time, but the schedule quality is not guaranteed. The effect of the algorithm is affected by the experience of users. Compared with heuristic methods and mathematical methods, CP can more easily search for schedules depending on the algorithm chosen by users. It is not restricted by any particular model formulation such as linear equations (Liu and Wang 2012; Heipcke 1999) and the schedule quality is guaranteed. Constraint programming is selected in this paper for construction and solution finding of the model based on the following reasons: (1) the highly constrained problems associated with project scheduling (Liu and Wang 2008), CP characteristics (which mean that constraints are naturally incorporated into the problem description; Chan and Hu 2002), CP flexibility in description of constraints, and CP capability in processing complex and special constraints (Heipcke 1999; Rossi et al. 2006; Liu and Wang 2012) suggest that CP is suitable for project scheduling optimization problems; (2) for LSM-based scheduling problems, prioritization of activities in linear scheduling problems becomes clear owing to the logical and sequential constraints in CP (Liu and Wang 2007); (3) the procedure for the solution of a problem does not require complex mathematical models and formula derivation, eliminating unavoidable simplification and ignorance, truthfully reflecting the original appearance of the problems and

ensuring the quality of the solution; (4) the model constructed through CP is flexible, and constraints and objection functions can be simply modified to meet various requirements without rebuilding the model (Liu and Wang 2007); and (5) in recent years, CP has been used increasingly in the industrial field (e.g., especially in scheduling and resource allocation; Heipcke 1999; Rossi et al. 2006; Liu and Wang 2007), but it has been used less in the field of civil engineering (Chan and Hu 2002). Therefore, as a reference and a new attempt, CP was applied to resource leveling optimization research based on LSM.

For the proposed model, the objective and variables were determined in the problem specification stage. In the research reported in this paper, the objective was considered as resource leveling, and the decision variables include the start date and resource usage of activities. To improve search effectiveness, fail-first and least-constraining-value heuristics were used for the order of variable and value. The order of variables is resource after the starting date. The order of values is taking values from small to large (Apt 2003, Rossi et al. 2006; Russell and Norvig 2009). To narrow the search space and find feasible solutions, considering the characteristics of arc consistency and the fact that it is the most popular and most consistently applied technique (Heipcke 1999; Apt 2003; Russell and Norvig 2009), the arc consistency checking technique is used for constraint propagation. Backtracking search is employed as the search strategy for problem solving. A search policy was used combining BT search and the arc consistency technique. The research approach is called maintaining arc consistency (MAC; Apt 2003; Rossi et al. 2006; Russell and Norvig 2009) and it is generally used in constraint programming software (Brailsford et al. 1999). *ILOG CPLEX Optimization Studio* was used and the ILOG OPL language was adopted as the model formulation language.

Two-Stage Scheduling Model for Resource Leveling

The proposed two-stage scheduling model for resource leveling is a CSP-based optimization model for linear project resource leveling that can automatically establish linear schedules with the target of resource leveling optimization. Optimal or near-optimal schedules can be obtained in a relatively short period of time using CP techniques. Establishment and optimization of linear schedules through this model is divided into two stages. Fig. 1 shows the optimization process of the two-stage scheduling model for resource leveling.

The first stage of optimization [Fig. 1(a)] is as described next. Based on the properties and constraints of activities, an activity was regarded in its entirety for optimization through the CSP-based scheduling model and the optimized schedule was denoted as P_{step1} [Fig. 1(b)]. Fig. 1(b) shows five activities, A–E. There was a minimum time constraint between A and C, with the time buffer denoted as $\min b_{A,C}$, and between C and E, with the time buffer denoted as $\min b_{C,E}$.

The second stage of optimization is as described next. Based on P_{step1}, the controlling activity path of P_{step1} was calculated through the CAP calculation model proposed by Harmelink and Rowings (1998). The bold part of Fig. 1(c) shows the CAP of P_{step1}. Rate float exists in the noncontrolling segments of activities. Through the float from the noncontrolling segment of these activities, the proposed CSP-based scheduling model was reused for further optimization of the noncontrolling activities and noncontrolling segments of activities, which further optimized the schedule denoted as P_{step2}. To ensure the continuity of resource usage, constraints were added to the controlling and noncontrolling segments of activities to ensure the continuity of construction activities during the second stage of the optimization process.
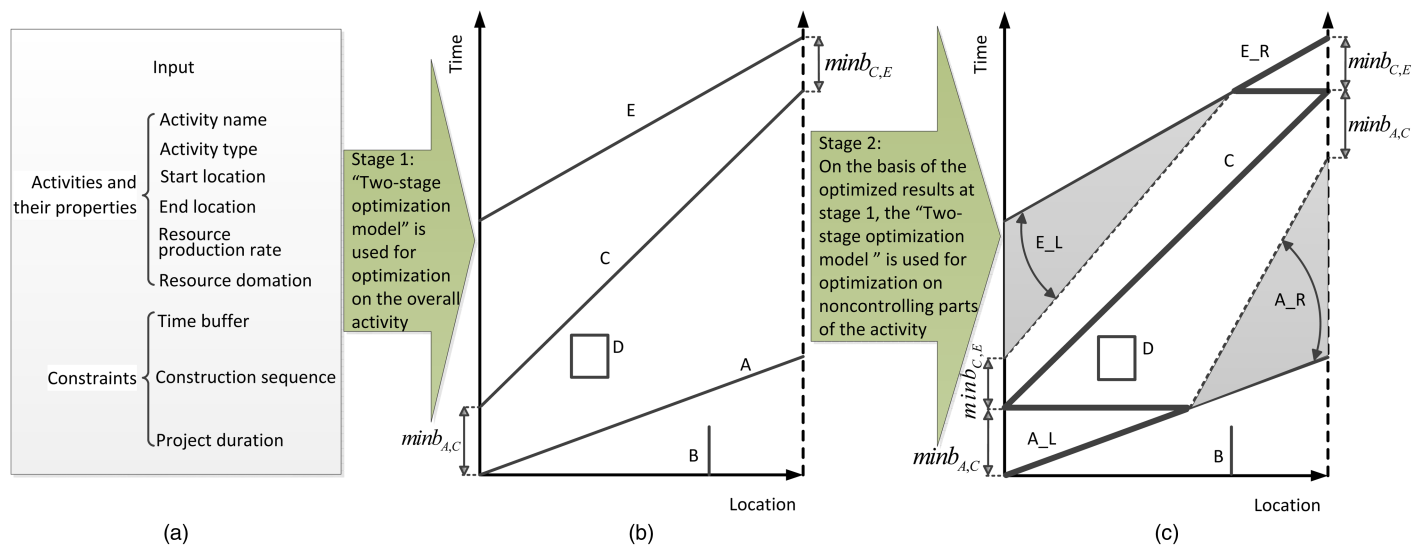
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Fig. 1. Optimization process of two-stage scheduling model for resource leveling

The noncontrolling segment of linear activities may appear in the left or right part of the activities as the noncontrolling segment E_L of activity E or the noncontrolling segment A_R of activity A, respectively [Fig. 1(c)]. Fig. 1(c) shows that the rate float of the corresponding activities for these two cases could be determined by the method proposed by Harmelink (2001). For example, the rates of the noncontrolling part A_R of activity A and noncontrolling part E_L of activity E could vary in the shaded region [Fig. 1(c)].

The fixed duration and logical relationship between activities (construction sequence and time buffer) were considered as constraints in this model. The rate and start time of the activity were regarded as variables to enhance the practicality and flexibility of the model.

The proposed scheduling model involves two concepts of rate, as follows:
1. Resource production rate, amount of work that can be accomplished by a unit of resource in unit time; and
2. Production rate, amount of work that can be accomplished during a unit time.

The start date of an activity is commonly restrained by the start date of the predecessor that has the constraint relationship with it and the buffer between them. In the case of a determined start date for the predecessor, the start date of the activity will be determined if the buffer between activities is fixed. Therefore, the flexibility of the start date for the activity is reflected in the flexibility of the buffer. The buffer in this model is a random value between the minimum and maximum time buffer. Under the condition that the constraint of maximum time does not exist between activities, no constraint of maximum time was added to the model so as to enhance the flexibility of the model.

In second-stage of the optimization of the model, the start date and rate for the controlling activities or controlling segments of activities became constants. To ensure continuity of construction activities, a constraint that the controlling and noncontrolling segments of activities should not be disconnected was added. In other words, the start date of the noncontrolling segment is a constant that equals the completion date of the controlling segment of activities when the controlling and noncontrolling segments of the activity are on the left and right, respectively; the completion date of the noncontrolling segment is a constant that equals the start

date of the controlling part of activities when the controlling and noncontrolling parts of the activity are on the right and left, respectively.

This model is more practical and flexible compared to those proposed in previous studies, as follows:
- The two-stage model was developed to overcome the drawbacks of single-stage optimization based on an analysis of previous resource leveling processes for linear schedules. The two-stage optimization sequence was set in accordance with the characteristics of different optimization stages to maximize the utilization of the rate float for activities, as follows: (1) the overall activities were optimized, and (2) the noncontrolling activities and noncontrolling segments of activities were optimized based on the rate float.
- The model was combined with CP techniques. Owing to the high efficiency of CP, no additional constraint was required for solving the model; the changing buffer was taken into account in this model, and the buffer without any additional constraint afforded the model strong flexibility and ensured the quality of the solutions.
- The description of constraints between activities was more flexible owing to the existence of partial-span linear activities and this in turn made the model more practical.

A scheduling system for two-stage resource leveling (described previously) was developed based on the proposed model and algorithm. Solving for the controlling activity path and automatic establishment of a resource leveling schedule were achieved using this system.

The subsequently described variables, constraints, and objective functions were used to develop the CSP-based model.

Constants

The values of the constants do not change during CSP problem solving; fa = first activity of project; la = last activity of project; cA_i = controlling segment of activity i; ncA_L_i = noncontrolling segment located to the left of controlling segment of activity i; ncA_R_i = noncontrolling segment located to the right of controlling segment of activity i; u_i = resource production rate of activity i; SD_i = start location of activity i; ED_i = end location of activity i; $q_i = ED_i - SD_i$ = total mileage of activity i; $\min r_i$ = minimum

resource usage of activity i; max r_i = maximum resource usage of activity i; min $b_{i,j}$ = minimum time buffer between activity i and activity j; $C_i \in \{block, linear\}$ = type of activity i; and D = total duration of project.

Decision Variables

The values of the decision variables were determined during the schedule search process; r_i = resource usage of activity i, and $r_i \in [min\, r_i, max\, r_i]$ is fixed for block-type activity; and $ST_i \in [0, D]$ = start date of activity i.

Decision Expressions

The expressions are $pu_i = r_i \times u_i$ = production rate of activity i; $d_i = q_i / pu_i$ = duration of activity i, which is fixed for block-type activity; $ET_i = ST_i + d_i$ = end date of activity i; $T_{i,x} = (x - SD_i)/pu_i$ = time needed for activity i to progress from location SD_i to location x; and

$$W_{i,j} = 0, ST_j \geq i \quad \text{or} \quad ET_j < i \qquad 1, ST_j < i \quad \text{and} \quad ET_j \geq i \tag{1a}$$

$$R_i = \sum_{j=1}^{n} r_j \times W_{i,j} \tag{1b}$$

where $W_{i,j}$ is a Boolean variable that identifies whether activity j is being executed on day i; and R_i = total resource usage of project on day i.

Constraints

Constraints can be divided into three types, as follows: (1) time buffer constraints between activities, (2) continuity constraints of activities, and (3) constraints of fixed duration for the entire project. Time buffer constraints between activities can be divided in accordance with the types of activities into those between full-span linear activities, those between a full-span/partial-span linear activity and a partial-span linear activity, and those between linear and block activities.

1. Time Buffer Constraint between Full-Span Linear Activities: If activity i and its predecessor h are full-span linear activities, the time buffer constraints between them can be described as the constraint between the starting dates and the constraint between the ending dates, which are respectively the left-hand and right-hand side constraints in the linear schedule diagram

$$ST_i \geq min\, b_{i,h} + ST_h \tag{2a}$$

$$ET_i \geq min\, b_{i,h} + ET_h \tag{2b}$$

Fig. 2 shows Cases 1 and 2.

2. Time Buffer Constraint between a Full-Span/Partial-Span Linear Activity and a Partial-Span Linear Activity: When there is a partial-span linear activity in two adjacent linear activities, the constraint can also be described as a left-hand or right-hand side constraint. The constraint can be subdivided into two cases depending on the spatial location of the activity, as follows:
   - Left-hand side constraint, when the starting location of activity i SD_i is less than that of its predecessor h SD_h
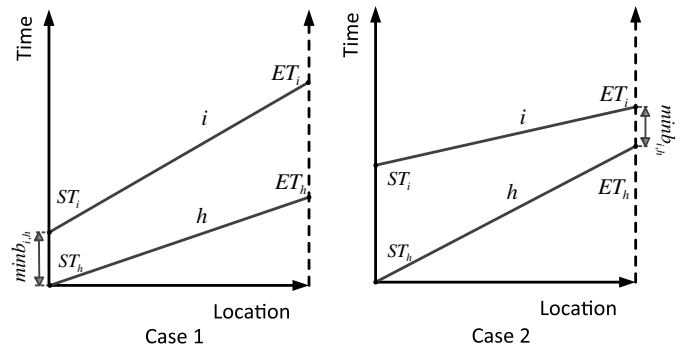

Fig. 2. Method for calculating constraints between full-span linear activities

$$ST_i + T_{i,SD_h} \geq ST_h + min\, b_{i,h} \tag{3}$$

This is Case 1 in Fig. 3.
   When the starting location of activity i SD_i is larger than that of its predecessor h SD_h

$$ST_i \geq ST_h + T_{h,SD_i} + min\, b_{i,h} \tag{4}$$

This is Case 2 in Fig. 3.
   - Right-hand side constraint, when the ending location of activity i ED_i is less than that of its predecessor h ED_i

$$ET_i \geq ST_h + T_{h,ED_i} + min\, b_{i,h} \tag{5}$$

This is Case 3 in Fig. 3.
   When the ending location of activity i ED_i is larger than that of its transitive predecessor h ED_i

$$ST_i + T_{i,ED_h} \geq ET_h + min\, b_{i,h} \tag{6}$$
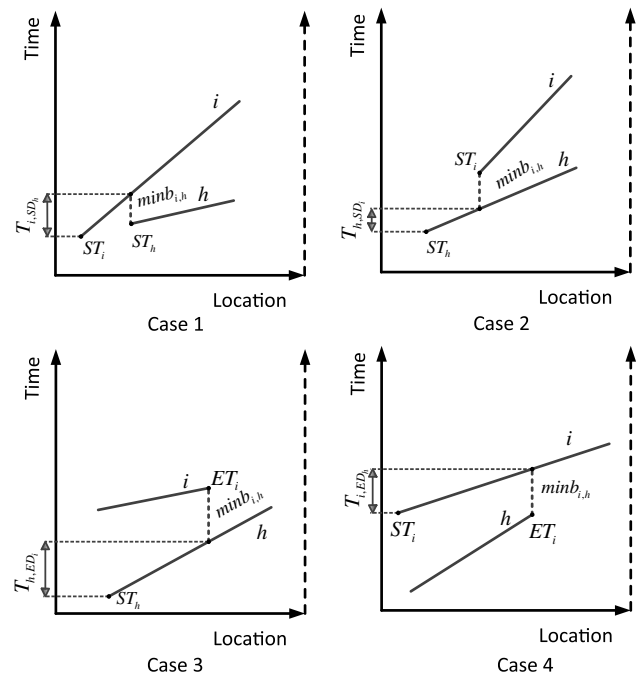
This is Case 4 in Fig. 3.

Fig. 3. Method for calculating constraints between a full-span/partial-span linear activity and a partial-span linear activity
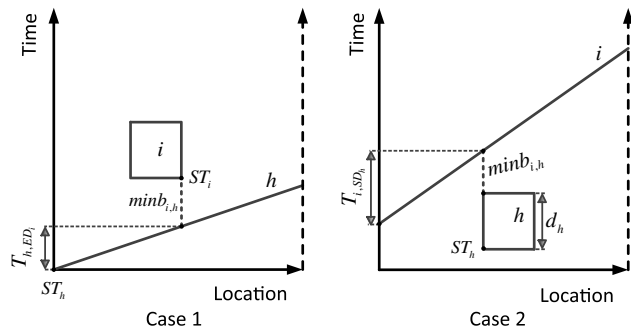
Fig. 4. Method for calculating constraints between linear and block activities

3. Time Buffer Constraint between Linear and Block Activities: When activity i is a linear activity, its predecessor h is a block activity

$$\mathrm{ST}_i \geq \min b_{i,h} + ST_h + T_{h,ED_i} \qquad (7)$$

This is Case 1 in Fig. 4.

When activity i is a block activity, its predecessor h is a linear activity

$$ST_i \geq \min b_{i,h} + ST_h + d_h - T_{i,SD_h} \qquad (8)$$

This is Case 2 in Fig. 4.

4. Constraint of Fixed Duration:

$$ST_i \geq 0 \qquad (9a)$$

$$ET_i \leq D \qquad (9b)$$

$$ET_{la} = D \qquad (9c)$$

$$ST_{fa} = 0 \qquad (9d)$$

5. Continuity Constraint of Activities: The noncontrolling segment of an activity needs to be adjusted in second-stage optimization of the model. To ensure continuity of construction activities, an additional continuity constraint on the noncontrolling segment of the activity is required, which is indicated as the controlling and noncontrolling segments of the activities cannot be disconnected in the LSM diagram.

The completion date of the noncontrolling segment located to the left of the controlling segment of an activity should be equal to the starting date of the controlling segment of the activity

$$ET_{ncA\_L_i} = ST_{cA_i} \qquad (10)$$

The starting date of the noncontrolling segment located to the right of the controlling segment of an activity should be equal to the completion date of the controlling segment of the activity

$$ST_{ncA\_R_i} = ET_{cA_i} \qquad (11)$$

Objective Function

A previously proposed objective function (Georgy 2008) was used for the two-stage scheduling model to ensure minimum deviation in daily total consumption of resources. The deviation in resource consumption was expressed as the sum of the absolute values for the differences between the resource consumptions of 2 days (adjacent)

$$\mathrm{Min} \sum_{i=1}^{D-1} |R_{i+1} - R_i| \qquad (12)$$

Model Verification

In the research reported in this paper, the C# language was used for programming the two-stage scheduling system for resource leveling under the *Visual Studio* development environment. The system includes three modules, as follows: (1) data input, (2) scheduling, and (3) schedule display. The scheduling module is the core module of the system. *ILOG CPLEX Optimization Studio* was integrated for developing the scheduling module described previously, and ILOG OPL modeling language was also used. The graphical interface of the display module was drawn based on *MapXtreme*. *SQL Server* was used as the database.

A shared instance of a highway construction project (Georgy 2008; Mattila and Abraham 1998) was adopted for verifying the effectiveness of the proposed model and algorithm, and the superiority of the current model was demonstrated through a comparison. The entire project consists of 50 stations and nine activities, and it has a total duration of 38 days; Table 1 lists more detailed attributes.

The results of the proposed two-stage scheduling model for resource leveling are as described next.

Table 1. Highway Project Attribute Data

Activity	Type	Buffer		Start location	End location	Minimum resource	Maximum resource	Prod/res/day
Ditch excavation A	Line	A-B	2	0	50	1	3	10/3
Culvert installation B	Block	B–/	0	42	42	1	1	3 days, duration
Concrete pavement removal C	Line	C–A	2	0	50	2	7	0.8334
		C–D	2					
Peat excavation and swamp backfill D	Block	D–E	0	8	12	8	8	3 days, duration
Embankment E	Line	E–C	2	0	50	2	7	1.25
Utility work F	Line	F–E	2	30	50	2	4	5
Sub-base G	Line	G–F	2	0	50	4	10	25/39
Gravel H	Line	H–G	2	0	50	4	10	1.25
Paving I	Line	I–H	2	0	50	4	10	25/12

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Table 2. First-Stage Optimization Results

Activity	Resource	Start date	End date	Duration
Ditch excavation	2	0	8	8
Culvert installation	1	0	3	3
Concrete pavement removal	5	3	15	12
Peat excavation and swamp backfill	8	15	18	3
Embankment	7	18	24	6
Utility work	2	24	26	2
Subbase	8	24	34	10
Gravel	4	26	36	10
Paving	7	34	38	4
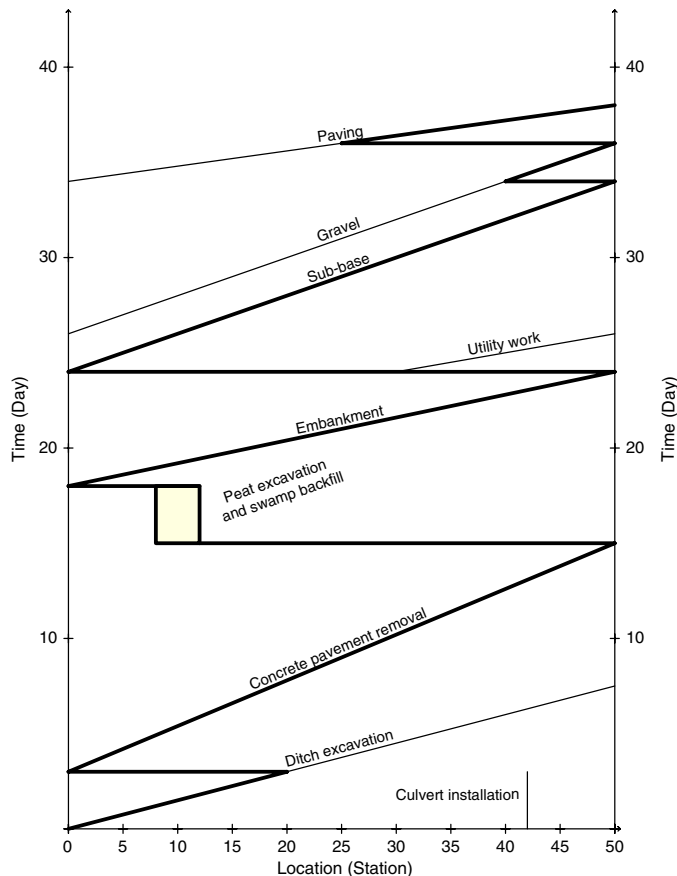
Fig. 5. First-stage optimization LSM diagram

First-Stage Optimization

Based on the data (Table 1), the schedule P_1 was established for the project by using the proposed scheduling model and its two-stage scheduling system for resource leveling. In the specific process of solving, the operation time was set as 2 s. Table 2 shows the data generated for the schedule. Table 2 indicates that the schedule satisfies the constraints of the 38-day fixed duration and the time buffer between activities. The corresponding objective function value is calculated to be 20.

Fig. 5 shows the corresponding LSM diagram of the first-stage optimization result generated by the two-stage scheduling system for resource leveling.

Second-Stage Optimization

In second-stage optimization, the CAP of P_1 was solved based on the model of Harmelink and Rowlings (1998). The CAP of P_1 was considered the basis of second-stage resource leveling optimization. Fig. 5 shows the CAP of P_1 as obtained through the two-stage scheduling system (indicated in bold).

Based on this CAP, an activity was divided into the controlling and noncontrolling segments; Table 3 lists the attribute data of the divided activities. The resource usage and starting date for the controlling activities and controlling segments of activities have been identified, and therefore the float does not exist. The noncontrolling activities and noncontrolling segment of activities still contain some float under the condition that the continuity constraints for the activities are satisfied, which is the basis for second-stage optimization. The activities (Table 3) still satisfy the constraint of the time buffer and unit resource productivity (Table 1).

Based on the data in Table 3, second-stage optimization was carried out using the proposed scheduling model and its scheduling system for two-stage resource leveling, with the resulting schedule being denoted by P_2. In the specific process of solving, the optimal schedule for the problem was obtained, which required 1 s. Table 4 shows the generated schedule data. Table 4 shows that the schedule satisfies the constraint of 38-day fixed duration and the time buffer between activities. The corresponding objective function value for the optimized schedule is calculated to be 18.

Fig. 6 shows the corresponding LSM diagram for the second-stage optimization result generated by the resource leveling scheduling system.

Comparison

Tables 5 and 6 show the contrasts between the initial schedules and optimization results for the highway project. Table 5 shows that the

Table 3. Activity Division Based on CAP

Activity	CAP	Start location	End location	Resource	Start date	End date	Duration
Ditch excavation-L	Controlling	0	20	2	0	3	3
Ditch excavation-R	Noncontrolling	20	50	—	3	—	—
Culvert installation	Noncontrolling	42	42	—	—	—	—
Concrete pavement removal	Controlling	0	50	5	3	15	12
Peat excavation and swamp backfill	Controlling	8	12	8	15	18	3
Embankment	Controlling	0	50	7	18	24	6
Utility work	Noncontrolling	30	50	—	—	—	—
Sub-base	Controlling	0	50	8	24	34	10
Gravel-L	Noncontrolling	0	40	—	—	34	—
Gravel-R	Controlling	40	50	4	34	36	2
Paving-L	Noncontrolling	0	25	—	—	36	—
Paving-R	Controlling	25	50	7	36	38	2

Table 4. Second-Stage Optimization Results

Activity	Start location	End location	Resource	Start date	End date	Duration
Ditch excavation-L	0	20	2	0	3	3
Ditch excavation-R	20	50	1	3	12	9
Culvert installation	42	42	1	0	3	3
Concrete pavement removal	0	50	5	3	15	12
Peat excavation and swamp backfill	8	12	8	15	18	3
Embankment	0	50	7	18	24	6
Utility work	30	50	2	24	26	2
Subbase	0	50	8	24	34	10
Gravel L	0	40	4	26	34	8
Gravel R	40	50	4	34	36	2
Paving L	0	25	7	34	36	2
Paving R	25	50	7	36	38	2

schedule obtained through the proposed model significantly differs from the initial schedule in addition to that suggested by Mattila and Abraham (1998) and Georgy (2008).

Table 6 shows the relevant parameters of different schedules. Both the initial schedule and each optimized schedule of the project satisfy the constraint of 38-day fixed duration and average consumption of eight units of resources. However, the corresponding objective function values for the schedule obtained by the proposed two-stage scheduling model are superior to the initial schedule in addition to those suggested by Mattila and Abraham (1998) and
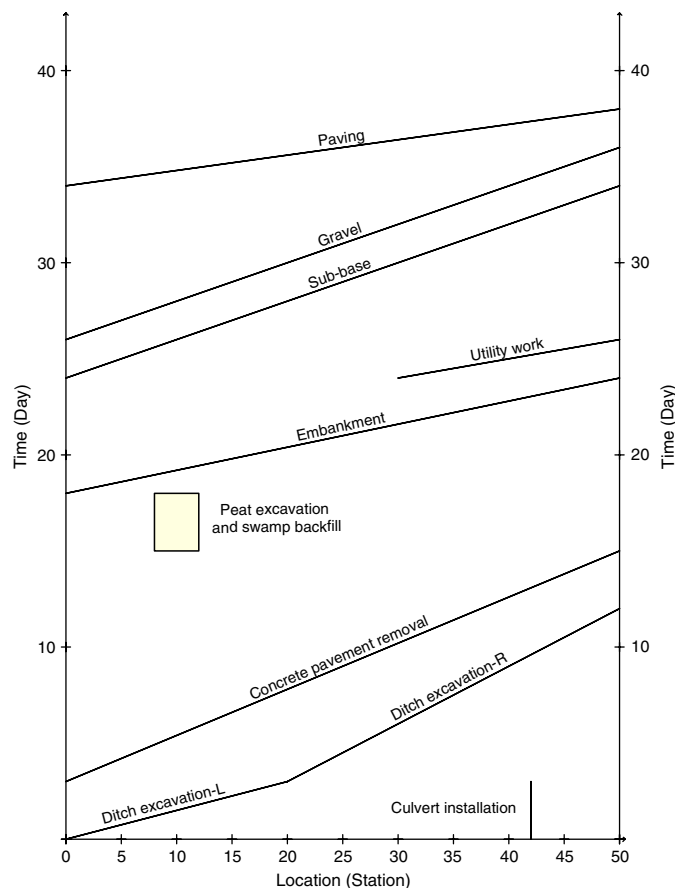
Fig. 6. Linear scheduling method for second-stage optimization

Table 5. Comparison of Resource Usage in Highway Project

Activity	Nonoptimized	Mattila and Abraham (1998)	Georgy (2008)	This paper, Stage 1	This paper, Stage 2
Ditch excavation	3	3/2	2	2	2/1
Culvert installation	1	1	1	1	1
Concrete pavement removal	4	4	7	5	5
Peat excavation and swamp backfill	8	8	8	8	8
Embankment	5	5	7	7	7
Utility work	2	2	3	2	2
Subbase	6	6	7	8	8
Gravel	8	4/8	7	4	4
Paving	8	8	9	7	7

Georgy (2008). A comparison of the objective function values shows that the schedule obtained by first-stage optimization of the proposed model is better than those obtained by previous models. The first-stage optimized schedule was further improved through second-stage optimization in the proposed model.

Table 6 indicates that the total resource consumption relative to the unoptimized original schedule increased by one (Mattila and Abraham 1998), 19 (Georgy 2008), nine (Stage 1 in this paper), and eight (Stage 2 in this paper). The increase in the total amount of resources is caused by changes in the resource configurations (allocation) and because total resource consumption occurs in the models neither as a constraint nor as the optimized target. Whereas the total amount of resources is basically added because the minimum duration unit of the actual optimized problem is 1 day, the minimum resource unit is one truck, which are both integers. Therefore, when some resources are used during a part of 1 day, they are summed as if they were used over the entire day (Mattila and Abraham 1998). In this case, this causes an increase in the total amount of resources. Taking activity F for instance, the resource usage of the unoptimized schedule and the optimized schedule given by Mattila and Abraham (1998) corresponding to F is 2/day, whereas that of the optimized schedule given by George corresponding to F is 3/day. However, the durations corresponding to F under the two resource configurations are the same, being 2 days. Although the total resource consumption of the optimized results in the research reported in this paper is increased compared with the unoptimized case, it is still significantly lower than the total resource consumption of the optimized results of Georgy (2008). In a future study, constraints on total resource consumption will be introduced or taken as one of the optimized targets of multiobjective optimizations.

Fig. 7 compares the resource loading curves between the optimized results obtained from this and previous models. Fig. 7 shows

Table 6. Comparison of Resource Profile Parameters in Highway Project

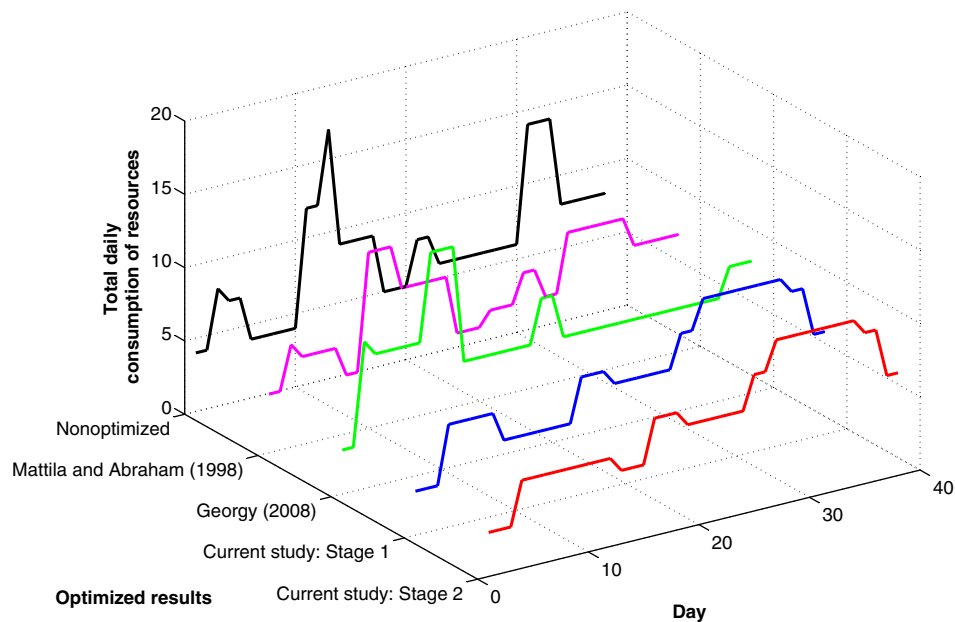| Parameters	Nonoptimized	Mattila and Abraham (1998)	Georgy (2008)	This paper, Stage 1	This paper, Stage 2
Total duration	38	38	38	38	38
Average resource usage	8	8	8	8	8
Sum of daily fluctuations	52	32	30	20	18
Total resource consumption	288	289	307	297	296

Fig. 7. Comparison of resource loading curves for the previous optimized results and the results obtained by the proposed model in the research reported in this paper

that after Stage 1 optimization of the model proposed in the research reported in this paper, the resource loading curve corresponding to the obtained schedule is smoother than the resource loading curves corresponding to the results obtained by the previous models and the resource consumption peak is reduced. However, the resource loading curve obtained in Stage 2 optimization for this model, based on the Stage 1 optimized results, provides further optimization (smoother).

Conclusions

In the research reported in this paper, a CSP-based two-stage scheduling model for linear project resource leveling was proposed based on the linear scheduling method for resource leveling problems subject to a constraint of fixed duration in linear projects. The model was combined with CP techniques. Owing to the high efficiency of CP, the proposed scheduler could obtain optimal or near-optimal solutions for resource leveling in a linear schedule in a relatively short period of time. Based on the proposed model and algorithm, a two-stage scheduling system for resource leveling of a linear schedule was developed for automatically establishing a linear schedule based on resource leveling. The graphical interface of the system is drawn based on *MapXtreme*. The effectiveness of the proposed model and algorithm was verified for a highway construction project reported previously (Mattila and Abraham 1998; Georgy 2008). A comparison shows that the results of the model proposed in the research reported in this paper are superior to those of previously proposed models.

Acknowledgments

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