Resource Management in Construction

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Abstract: Resource planning and management is one of the most important ingredients for competitiveness and profitability in today's construction industry. In order to control costs, equipment and labor should be utilized in the most efficient way possible. This can be achieved by minimizing the total cost of leased resources under the constraint of maximum and most efficient use of owned equipment and contracted labor force. This paper presents a mixed-integer linear programming model for the management of resources throughout the project life. Based on the Critical Path Method time analysis, the model derives the schedule for equipment rentals and transient resources, as well as the utilization scheme for owned equipment and other available resources. The model can be used as an estimating tool for multi-project resource planning and sharing, and as a means to implement the most efficient utilization of resources throughout the duration of the whole project.

Introduction

Most contractors use both owned and leased construction equipment, as confirmed by a recent study (3). The allocation of resources of different types to a construction project is a difficult managerial problem, particularly when construction equipment has to be shared among a number of project sites. Timing adequately the use of different pieces of equipment on a given project is an important cost control issue, since an inadequate allocation and scheduling of resources can lead to equipment idleness and consequently higher costs of leased equipment, due to the inefficient use of both leased and owned equipment.

The purpose of this paper is to plan and schedule construction activities according to an optimal resource allocation scheme. This scheme is derived by using a model that minimizes the cost of leased resources (equipment, and possibly labor) over the project life, given a certain level of resources available, such as owned equipment. The model can be used by both private contractors and departments of public works, in that: (1) All resource types can be envisioned; and (2) the objective function and the constraints are relevant for the organization of any construction project.

Resource Management Model

Scheduling and Resource Allocation in Construction.—The scheduling of construction activities in any fairly complex project is undertaken using the Critical Path Method (CPM). A comprehensive analysis of the method and its application in construction practice can be found in (1). Although the CPM is a time analysis method, the integration of

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resource allocation tasks has been previously achieved by simply scheduling construction activities in such a way that resource needs can be matched throughout the project life. This is usually done by heuristically and sequentially shifting activities the availability of resources "as needed," resource allocation is necessary to define a feasible schedule. The model presented hereafter uses the CPM time analysis as a starting point to a more comprehensive resource management and scheduling model.

One of the major weaknesses of the Critical Path Method (CPM) is the fact that activities cannot be intermittent. It is often more cost effective to stop a specific activity for a certain period of time, thus allowing its resources to be used in another activity. This saves both time and money. By shifting activities within their allowable float, an optimal resource utilization schedule can be developed.

Formulation of Model.—This comprehensive resource management model has a mixed integer-linear programming structure. It is based on the minimization of the total costs of leasing additional resources, under the time constraints obtained from the time analysis of the CPM.

Resource analysis and allocation problems have been extensively studied in the literature. A feature common to these problems is the recognition that the resources involved in carrying out a project can influence scheduling either by their limited availability or by other kinds of restrictions. Four classes of resource analysis problems can be distinguished for project scheduling purposes:

1. Resource loading, which produces, for a given project schedule, time charts regarding the usage of the various resources required by the project activities. These charts are then checked against resource availabilities to establish whether the project is feasible.
2. Resource leveling, which focuses on the time pattern of resource usage. In optimizing scheduling decisions, no implicit costs are considered. *Rather, it is implicitly assumed that varying the usage of a specific* resource entails significant costs because of charges such as hiring, firing, overtime, and idle labor or equipment. For large networks, resource leveling requires the aid of a computer. Leveling procedures are generally heuristic.
3. Resource constrained problems, which address the issue of allocating limited resources to competing activities in order to either achieve minimal project completion time or the minimal total cost schedule.
4. The time-cost trade-off problem is centered on the idea that the duration of some activities can be cut down if additional resources are allocated to them.

The use of quantitative methods in construction management is described in Ref. 2. Uses of linear optimization in construction management are also presented in Ref. 11. In Ref. 6, linear programming is used for sharing resources in linear construction where a fairly simple construction logic is repeated successively. This work was later discussed in Ref. 8. The optimization model presented herein uses the CPM output as an anchor for the selection of the most cost-effective schedule of construction operations.

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It is formulated as a problem combining resource-constrained, resource-leveling and time-cost trade-off themes in a structure that fits the reality of resource constraints in the construction industry. An assumption is made that the project duration required by the owner will be met.

Objective Function.—The objective of the model is to minimize the cost of leasing additional resources, primarily in construction equipment. However, under the assumption of an open shop labor market, labor resources can be included in the set of resource types.

For all resource types ($r \in R$), activities ($j \in J$) and days ($i \in I$), the problem can be stated as

$$\text{Minimize } Z = \sum_{r \in R} \sum_{j \in J} \sum_{i=ES_j}^{LF_j} C_{r,j,i} RR_{r,j,i} \quad (1)$$

where $C_{r,j,i}$ = cost of leasing an additional unit of resource type r to use it in activity j on day i; $RR_{r,j,i}$ = number of leased additional units of resource type r to be allocated to activity j on day i; R = set of all types of resources; J = set of all activities; I = set of all days within the project duration; ES_j = earliest start of activity j; and LF_j = latest finish of activity j.

Resource Requirement Constraints.—It is assumed that daily resource requirements of any activity are predetermined. In Ref. 9, it was found that a "best" crew combination for construction operations can be selected.

Resource constraints are defined differently for critical and noncritical activities.

a. *For critical activities*: Critical activities (i.e., activities on the critical path), have a completely defined time schedule.

The sum of the number of leased units of a given resource and the number of available units of the same resource to be allocated to a critical activity on any day, should equal the activity requirements on that day. For critical activity j, the following constraint is written on day i of the activity duration, and for resource type r required as

$$RR_{r,j,i} + R_{r,j,i} = n_{r,j} \quad (2)$$

where $R_{r,j,i}$ = number of available units of resource type r to be allocated to a critical activity j on day i; and $n_{r,j}$ = total number of required units of resource type r to be allocated to a critical activity j on any day within its duration.

b. *For noncritical activities*: Noncritical activities have a time "float," which is the difference between their earliest and latest start (or finish). They only need to be "active" for a certain number of days (activity duration) between the earliest start and latest finish. In order to control whether an activity is "active" on a given day, a binary integer variable which takes the value 1 or 0 to represent, respectively, an active or an idle day, is introduced in a constraint similar to Eq. 2. The resource requirement constraint for a noncritical activity j on a day i between its earliest start and latest finish, and for any required resource type r, can be stated as

$$(n_{r,j} \cdot \text{ING}_{j,i}) - RR_{r,j,i} - R_{r,j,i} = 0 \quad (3)$$

where $\text{ING}_{j,i}$ = A (0/1) variable that controls the status of activity j on day i.

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Time Constraint.—For any activity j, ES_j, EF_j, LS_j and LF_j represent, respectively, its earliest start, latest start, earliest finish and latest finish days. D_j represents the activity duration.

Again, it is necessary to differentiate between critical and noncritical activities.

a. *Critical activities*: Since the duration of critical activities is indirectly implied in the preceding resource constraints, no additional time constraints are needed.

b. *Noncritical activities*: The total number of "active" days for activity j should be equal to D_j:

$$\sum_{i=ES_j}^{LF_j} \mathrm{ING}_{j,i} = D_j \qquad (4)$$

Resource Availability Constraints.—The sum of all available resource units allocated to different activities on the same day should not exceed the total number of units available on that day. This can be stated as

$$\sum_{j\in J} R_{r,j,i} \leqq Av_{r,i} \quad \text{for all } r,\, i \qquad (5)$$

where $Av_{r,i}$ = number of units of resource type r available on day i.

Network Logic.—Network logic constraints are not required for the path(s) of critical activities since their network logic is implemented within resource requirements constraints of the type in Eq. 2. However, for those paths involving noncritical activities a catalyst integer variable is introduced to preserve the network logic (precedence relationships). In a precedence relationship, a leading activity is distinguished from a dependent activity.

The idea behind this technique is to sequentially count the number of positive integers assigned to a leading activity at different points in time and compare it to the activity duration. As long as the leading activity l, is not completed, all dependent activities cannot start. In other words, as long as the sum of all integers from ES_l to day m is less than D_l, integer variables assigned to dependent activities for day $(m + 1)$ have to equal zero (see Fig. 1).

The following two groups of constraints related to every leading activity l make these conditions possible:

$$\left(\sum_{i=ES_l}^{m} \mathrm{ING}_{l,i}\right) + B\,\mathrm{CAT}_{l,m+1} \geqq D_l \qquad (6)$$

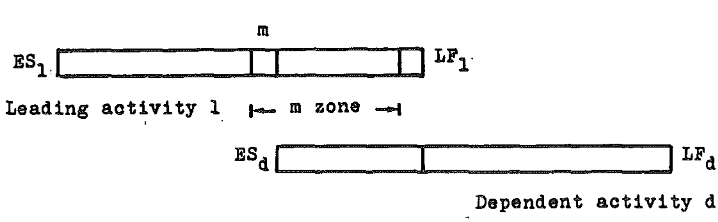

FIG. 1.—Leading/Dependent Activities

TABLE 1.—Network Logic Constraint

Case of (1)	$CAT_{l,m+1} =$ (2)	$\sum_{d \in Dep_l} ING_{d,m+1} =$ (3)
$\sum_{i=ES_j}^{m} ING_{l,i} < D_l$	1	0
$\sum_{i=ES_j}^{m} ING_{l,i} = D_l$	Free	Free

$$\sum_{d \in Dep_l} ING_{d,m+1} + B\, CAT_{l,m+1} \leqq B \quad \text{(7)}$$

for all leading activities and m such that $m \in M_l$, where $ING_{l,i}$ = integer variable of the leading activity l on day i; M_l = set of days that go from the earliest start day of all dependent activities minus 1 to the latest finish day of leading activity l minus 1 ($ES_d - 1 \ldots LF_l - 1$); B = large positive number; $CAT_{l,m+1}$ = (0/1) integer variable to determine whether $ING_{d,m+1}$ should necessarily be zero; Dep_l = set of all activities dependent on the leading activity l; D_l = duration of the leading activity; and $ING_{d,m}$ = integer variable of the dependent activity d on day m.

Eq. 6 states that if the sum of integer variables ($ING_{l,i}$) of the leading activity l until day m is less than its duration D_j, the integer variable $CAT_{l,m+1}$ has to equal l. This forces the sum of integer variables $\Sigma_{d \in Dep_l} ING_{d,m+1}$ in Eq. 7 to be zero.

However, once the leading activity is completed, (i.e., $\Sigma_{i=ES_l}^{LF_l} ING_{l,i}$ equals D_l), the integer variable $CAT_{l,m+1}$ is released (i.e., it does not have to equal 1 anymore). This makes it possible for the integer variables $ING_{d,m+1}$ related to dependent activities d on day $(m + 1)$ to take the values zero or 1. However, a nonzero $CAT_{l,m+1}$ will restrict the dependent activities of l, due to Eq. 7.

The summary of this relationship between integer variables is shown in Table 1.

Constraints for Continuous Activities.—If all previous constraints are applied to a project the resulting schedule will fulfill resource requirements, time constraints, and network logic. Also, all activities (except critical activities) are allowed to be intermittent. However, some activities, such as pumping or dewatering, have to be continuous. The following two groups of constraints are used for the case of a continuous activity j:

TABLE 2.—Continuous Activity Constraint

Case of (1)	$USE_{j,t} =$ (2)	$\sum_{i=t+D_j}^{LF_j} ING_{j,i} =$ (3)
$ING_{j,t} = 1$	0	0
$ING_{j,t} = 0$	Free	Free

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$$\mathrm{ING}_{j,t} + S\,\mathrm{USE}_{j,t} \leqq 1 \quad (8)$$

$$\left(\sum_{i=t+D_j}^{LF_j} \mathrm{ING}_{j,i}\right) - B\,\mathrm{USE}_{j,t} \leqq 0 \quad (9)$$

for all $t = ES_j$ through $LF_j - D_j$, where S = small number between 0 and 1. ($0 < S < 1$); and $\mathrm{USE}_{j,t}$ = integer variable that makes all days starting at $t + D_j$ inactive, if day t is active.

Table 2 summarizes the mechanism related to continuous activities.

Application of Model

The model was applied to a simple problem consisting of four resources, manpower (W), and equipment types X, Y, and Z. The available number of units of different resources, and the cost of leasing an additional unit per day are given in Table 3.

The project summary is given in Table 4. The activity-on-arrow notation is assumed. For example, activity A is also activity 1-2, has a duration of 8 days, is continuous, and has daily resource requirements of 4, 1, 1, and 0, respectively.

Figs. 2–4 represent the time and resource schedules, respectively, for the earliest start, the latest start and the minimum cost solution. In the

TABLE 3.—Resource Summary

Resource (1)	Number of units available (2)	Leasing cost per unit (dollars) (3)
W	18	25
X	1	100
Y	1	300
Z	1	200

TABLE 4.—Project Summary

Activity (1)	Nodes $I \rightarrow$ (2)	Nodes J (3)	Duration (days) (4)	Mode (5)	Daily Resource Requirements: Manpower (W) (6)	Equipment X (7)	Equipment Y (8)	Equipment Z (9)
A	1	2	8	Continuous	4	1	1	0
B	1	3	7	Continuous	10	0	0	1
C	1	5	12	Intermittent	5	0	1	0
D	2	3	4	Continuous	6	0	0	0
E	2	4	10	Intermittent	7	1	0	0
F	3	4	3	Continuous	5	0	1	0
G	3	5	5	Intermittent	8	0	0	0
H	3	6	10	Intermittent	7	0	1	0
I	4	6	7	Continuous	11	0	1	1
J	5	6	4	Continuous	3	1	0	0

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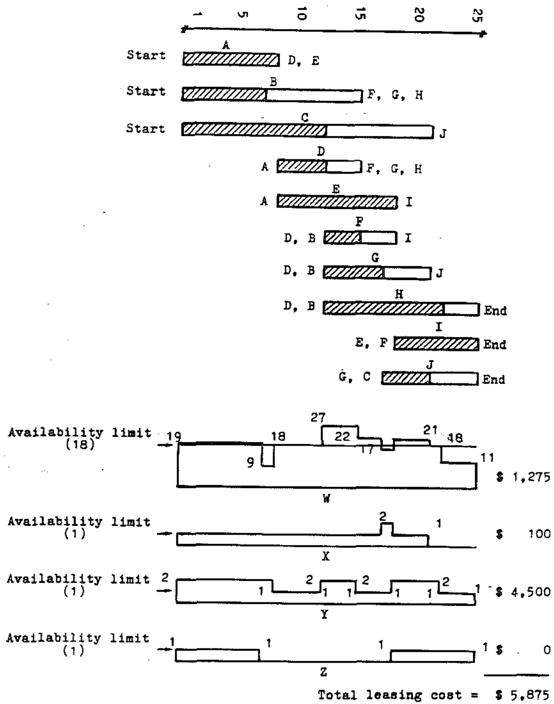

FIG. 2.—Earliest Start Schedule

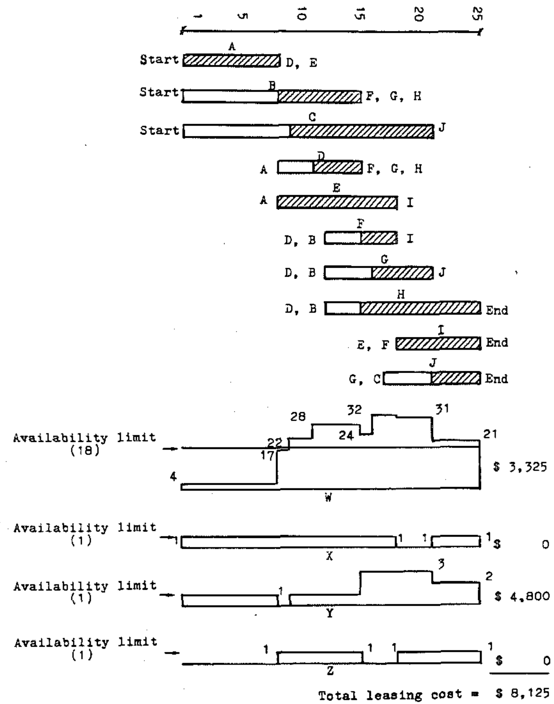

FIG. 3.—Latest Start Schedule

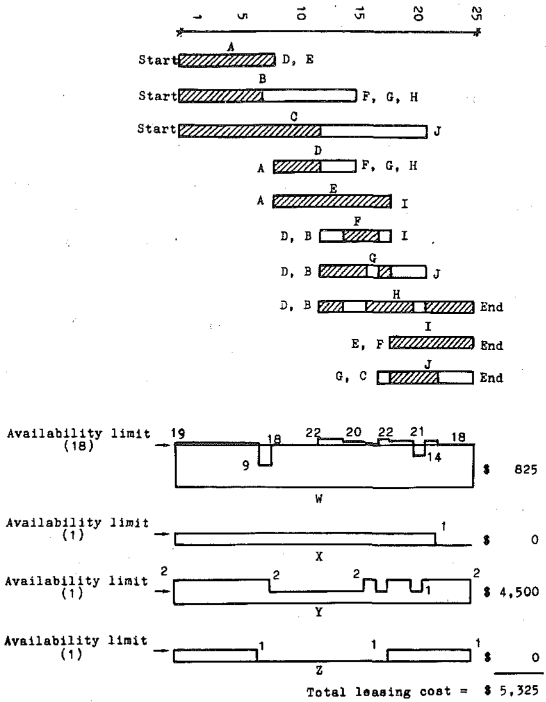

FIG. 4.—Minimum Leasing Cost Schedule

upper portion of these figures, the time ranges for activities are diagrammed by bars, of which the shaded part is the "active" portion of the range, i.e., the time when the activity is actually performed. The activity name is shown, respectively, to the left and to the right of the bar. In the lower part of these figures, resource profiles are given over the project life for resource types W, X, Y, and Z. The horizontal axis is the time axis. To the right of each resource profile, the leasing costs for different resources are given, with the total leasing cost shown at the bottom of each figure.

The total leasing cost related to the earliest start schedule, as given by the CPM time analysis was found equal to $5,875. Fig. 2 diagrams the time and resource schedules of the earliest start case. The latest start case, diagrammed in Fig. 3, required $8,125 in leasing costs.

Using the minimum leasing cost model implemented on the LINDO LP system, a total leasing cost of $5,325 was obtained. As shown in Fig. 4, the minimization model made it possible to take advantage of the intermittent activities to level off resource requirements, a fact that explains the cost saving of about 10% from the earliest start solution and about 35% from the latest start schedule.

Flexibility of Model and Limitations

The preceding formulation of the resource management model is quite

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flexible in that it can be slightly modified to take into account variations from the underlying assumptions of the model.

Nonuniformity of Production Rates.—Instead of assuming a constant daily rate of production, the model can be changed to control and vary the production rate, while preserving the general time frame for different activities.

Updating Possibilities.—The model can be easily modified to take into account a change in available resources, due to project related conditions or to external conditions. Also, changes in the market prices of resources and change orders can be translated in a change in the affected constraints.

Budget Limitations.—For financial and risk control purposes, a contractor might wish to limit the total daily or weekly expenditures to a certain level Bud_i (Budget for day or week i). This constraint can be stated as

$$\sum_{r\in R}\sum_{j\in J} C_{r,j,i}\,RR_{r,j,i} \leqq \mathrm{Bud}_i \quad \text{(10)}$$

Sensitivity Analysis.—The model makes it possible to evaluate the time and cost impact of such measures as increasing the labor force engaged in some activity, subcontracting some portion(s) of the work, using an equipment type or method, or varying the production rate for some particular activity. The CPM time analysis related to any such scenario can be used to generate the resource and activity schedule, as well as the costs involved. Such a step can be performed during the estimating stage, and subsequently during the planning and construction stages.

"Floating" Whole Project.—If the project duration determined by the CPM analysis is shorter than the duration required by the owner, the difference could be used as overall float for the project. This float can be added to the latest finish of each activity. As a result of this additional float, critical activities cease to be critical and are treated, in the model, as noncritical activities. The advantage of the model is that critical activities can now be intermittent, uniform or nonuniform rather than simply continuous. This can lead to major savings in shifting resources, according to the minimum cost solution.

Transportation Costs.—In the foregoing model, a constant daily leasing cost for resources, is assumed. In practice, transportation and mobilization costs are often considerable for heavy equipment. For this reason the objective function can be modified to include transportation costs. The modified objective function becomes

$$\mathrm{Min}\ Z = \sum_{r\in R}\sum_{j\in J}\sum_{i=ES_j}^{LF_j} C_{r,j,i}\,RR_{r,j,i} + \sum_{r\in R}\sum_{i=ES_j}^{LF_j} T_{r,i}\cdot F^{+}_{r,i} \quad \text{(11)}$$

The following constraint is added to the previous set of constraints:

$$\sum_{j\in J} RR_{r,j,i} - \sum_{j\in J} RR_{r,j,i-1} = F^{+}_{r,i} - F^{-}_{r,i} \quad \text{for all } r,\ i \quad \text{(12)}$$

where $T_{r,i}$ = cost of transporting one unit of resource type r on day i; and $F^{+}_{r,i}$ and $F^{-}_{r,i}$ = two non-negative variables, which cannot be both strictly positive.

Limitations of Model.—The limitations of the model are issues of problem dimension. As the project increases in complexity, the number of integer variables becomes too large to handle with existing branch-and-bound/LP software capabilities. However, systems such as LINDO and MPSX have sufficient capabilities for the resource optimization of small networks.

One way to solve the dimensionality problem is to decompose the network in subnetworks of activities between two major milestones. Also some of the activities might not require any resource scheduling, as their resource utilization scheme is fairly simple. The purpose of such measures is to structure the resource optimization model by selecting the activities, the relevant time frames and subdivisions, in order to reduce the dimensionality of the problem.

Summary and Conclusions

In this paper, a comprehensive resource management model was presented for scheduling construction projects based on an optimal resource utilization scheme. The model objective is to minimize the costs of leasing additional resources, given a certain level of resource availability. The model has the capability of mapping continuous, intermittent, uniform and nonuniform activities, and therefore preserves the integrity of construction operations.

This model can be used as an estimating tool, since the logistics of the construction project are the output of the resource optimization. It can be used in multi-project planning, by running a number of projects as a single profit center. This is made possible by allocating available resources among different projects and evaluating and comparing different resource allocation schemes.

The model can be used continuously in phased construction and can be updated as new information is gathered after the completion of successive milestones.

In large projects, the model can be used to help plan the preliminary resource requirements and make lease versus buy decisions.

Because of its fully defined resource schedules, the model can be used for cost control purposes, as durations can be tracked to any of the resource or time parameters, which makes it possible to correct and predict project cost changes.

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Appendix II.—Notation

The following symbols are used in this paper:

$Av_{r,i}$ = available number of units of resource type r on day i;
B = large positive number;
Bud_i = allowable budget limit on day i;
$\mathrm{CAT}_{l,m+1}$ = (0/1) catalyst integer variable used to prevent dependent activities from starting prior to completion of leading activity;
$C_{r,j,i}$ = cost of leasing one unit of resource type r to use in activity j on day i;
D_j = duration of activity j;
D_l = duration of leading activity 1;
Dep_l = set of all activities dependent on leading activity 1;
ES_j = earliest start of activity j;
$F^+_{r,i}$ = non-negative variable to account for additional requirements for resource type r from day $(i - 1)$ to day i;
$F^-_{r,i}$ = non-negative variable to account for decreasing requirements for resource type r from day $(i - 1)$ to day i;
I = set of all days within project duration;
$\mathrm{ING}_{d,m}$ = integer variable of dependent activity d on day m;
$\mathrm{ING}_{j,i}$ = (0/1) integer variable that controls non-working/working status of activity j;
$\mathrm{ING}_{l,i}$ = same as $\mathrm{ING}_{j,i}$ for leading activity l on day i;
J = set of all activities;
LF_j = latest finish of activity j;
l = index for leading activity;
M_l = set of days that go from earliest start of dependent activities −1 to latest finish of leading activity −1 $(ES_d - 1 \ldots LF_l - 1)$;
m = day number varying between earliest start of dependent activities −1 to latest finish of leading activity −1 $(ES_d - 1 \ldots LF_l - 1)$;
$n_{r,j}$ = total required number of units of resource type r to be allocated to activity j on any day within its duration;
R = set of all types of resources;

$R_{r,j,i}$ = available number of units of resource type r to be allocated to critical activity j on day i;

$RR_{r,j,i}$ = number of additional units of resource type r to be allocated to activity j on day i;

S = small value, $0 < S < 1$;

$T_{r,i}$ = cost of transporting one unit of resource type r on day i; and

$\mathrm{USE}_{j,t}$ = integer variable for continuous activity j that makes all days starting at $t + D_j$ inactive, if day t is active.

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