Flexible Resource-constrained Discrete Time-cost Trade-off Problem Considering Resource Transfer

Haobo Zou, Guohua Zhou

School of Economics and Management, Southwest Jiaotong University, China
zouhaobo88@163.com, ghzhou@126.com

Abstract

With the acceleration of global infrastructure construction in recent years, numerous repetitive construction projects are under planning or construction. Resources need to be transferred between units in the construction process. This transfer will lead to a large amount of time and cost consumption, and the existing research on discrete time-cost trade-off problem (DTCTP) of repetitive projects has paid little attention to this issue. This paper introduces an improved resource transfer scheme (DTCTP-rt) considering calculable resource transfer costs, and the calculation results show that this method can obtain a more practical solution. After introducing resource transfer, resource demands conflicts between units become more intense. In order to address this problem, the concept of flexible resource constraint (FRC) is introduced to form FRCDTCTP-rt. The resource constraint is no longer regarded as a fixed constant, but allowed to float arbitrarily in an interval. The calculation results show that considering FRC provides managers with more and better feasible choices.

Keywords: Repetitive project, Resource transfer, Time cost trade-off, Flexible resource constraint, NSGA- II

1 Introduction

Repetitive projects play a significant role in the construction industry [1]. Examples of these projects are railways, pipelines, high-rise buildings, highways and bridges. To increase efficiency in terms of time and cost of this type of project is part of the most important efforts. In response to these challenges, literature has defined these problems as discrete time-cost trade-off problem (DTCTP) in CPM (critical path method). However, the application of CPM in repetitive projects is limited [2], several DTCTP scheduling methods applicable to repetitive projects have been developed, such as, linear programming, dynamic programming, genetic algorithms, and mixed-integer programming [3-6]. It has been considered by various scheduling optimization problems too, for example, multi-mode resource constraint [7-9], resource levelling [10-11], soft-logic method [12-14], uncertain [15-16], and minimization of total interruption cost [17].

The scheduling is handled to schedule each unit without recourse transfer. It helps to obtain practical results while reducing the duration and cost. The majority of approaches proposed above are based on the principle that resources can be transferred without any expense in time or cost. In most realistic cases, resource transfer increases project time or risk of project delays. Ignoring resource transfer will lead to impractical planning. In order to ensure the effective use of resources, the transfer times and costs need to be considered earlier in the planning stage [18]. In repetitive projects, activities consist of repetitive units at different locations. Transferring work should be performed after a unit is expected to be completed to transport resources from the current unit to the next one [19]. Huang, et al. (2016) especially consider resource transfer times and costs in repetitive projects. Its main purpose is to study repetitive projects without linear characteristics (the construction of multiple buildings) and it is considered that the transfer cost of linear activity (bridge engineering) is 0. Repetitive projects consist of activities repeated at different locations in the form of units. However, repetitive projects can be divided into linear and non-linear construction projects, and linear projects can also be divided into lines activities (bridge beam) and block/bar (excavation and other bridge foundations) [20]. The specific classification is shown in Figure 1.

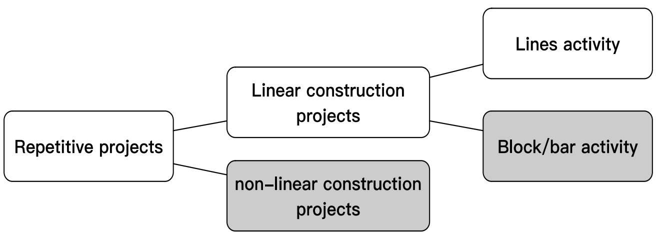

Figure 1. The specific classification of repetitive projects

This paper mainly optimizes the resource transfer

*Corresponding Author: Guohua Zhou; E-mail: ghzhou@126.com
DOI: 10.3966/160792642021012201019

mode of non-linear projects and block/bar activities because of the flexibility of resource transfer in non-linear projects and block/bar activities In Huang's model, resources can only be transferred between units with priority constraint, that is, after a unit is completed, resources can only be transferred to its successors. In practice, there are more ways to transfer resources. The comparison of resource transfer schemes is described in detail in Table 1.

Table 1. Resource transfer shemes in different literatures

Literatures	Resource transfer shemes	Remarks
Yang and Sum (1993, 1997) [21-22]	Resource transfer times between resource pool and projects	The cost of resource transfer is not considered in these studies
Debels and Vanhoucke (2006) [23]	Sequence-independent setup times	
Krüger and Scholl (2009, 2010) [24, 18]	Sequence-dependent transfer times between activities	
Adhau, et al. (2013) [25]	Sequence-dependent transfer between pool and activities and transfer among activities Asuming that resources can also be transferred from high to low priority activity and resources may be transferred from: one activity to one activity, many activities to one activity, one activity to many activities	
Suresh, et al. (2015) [26]	Asuming that resources are kept idle on that activity premises once activity is completed, until resource transfer is occurred	
Other literatures [27-29]	There is no in-depth discussion on the sheme of resources transfer	

Resource conflicts become more intense with resource transfer, then resource constraint have greater impact on scheduling schemes. Managers usually choose to adjust resource constraint to obtain multiple feasible solutions for comparison. In addition to the scheme of transfer, considering resource transfer will also increase the pressure of project resource constraint [30]. Because the resource transfer may occur at the same time as the activity execution process, the resource constraint (the initial amount of resources in the resource pool) will have a significant impact on the scheduling result [27]. However, existing studies regard resource constraint as a constant, without considering the influence of changes in resource constraint, although we can improve the performance-price ratio of schemes by choosing more appropriate resource constraint. The existing discrete time cost trade-off problem lead to a large amount of time and cost consumption, so we introduced an improved resource transfer scheme by considering the resource transfer costs. In this paper, a resource-constrained scheduling system with flexible resource constraint, denoted as FRC, is developed to resolve resource conflicts caused by resource transfer. Trying to reach a better overall results set, while the resource constraint floats arbitrarily in an interval.

This paper presents a discrete time-cost trade-off problem with flexible resource constraint considering resource transfer (FRCDTCTP-rt). Two new model were designed: 1) A new resource transfer scheme, which can obtain more practical results while further reducing the duration and cost of the project and resource transfer cost is considered in this model. 2) A flexible resource constraint model, aiming to deal with resource conflicts caused by resource transfer by adjusting resource constraint.

2 Material and Methods

The project that is described in this paper consists of L activities; each activity consists of N units. a_{ij} is a unit belonging to activity i (i=1, …, L) at location j (j=1, …, N). M_i is a set of feasible execution modes of activity i. Each unit is allowed to adopt different execution modes and denoted as $m_{a_{ij}}$ $(m_{a_{ij}} \in M_i)$. $d_{a_{ij}m_{a_{ij}}}$ denotes the duration of a_{ij} with the execution mode $m_{a_{ij}}$. The project has K types of renewable resource, and the initial availability of the resource k in each time slot is R_k^0. Managers can adjust R_k^0 to obtain a more cost-effective solution and the adjusted part is recorded as R_k'. The demands of resource k in units in each period t shall not exceed the resource constraint $(R_k^0 + R_k')$. Any increase or decrease in R_k' incurs costs which denoted as $FRCC_k$. The demands of resource k of a_{ij} in execution mode $m_{a_{ij}}$ is $r_{a_{ij}m_{a_{ij}}k}$. The resource k may be transferred from the resource pool to units and also from one or many resource provider unit (source) to resource receiver unit (destination), which will result in the increase of time (RTT) and cost (RTC). The magnitude of RTT depends on the the relative position between the source and destination, and the calculation of RTC is described later. $ST_{a_{ij}}$ and $ET_{a_{ij}}$ denote the start time and the finish time of unit j of activity i, respectively.

The objective of the flexible resource-constrained discrete time/cost trade-off problem with resource transfer (FRCDTCTP-rt) is to determine a set of results, which introduce resource transfer and satisfy flexible resource constraint. Feasible results with two objective function values project duration (Y_t) and cost (Y_c) are non-dominated solution [31].

2.1 Model Development

Owing to DTCTP is NP-hard problem, an algorithm framework called NSGA- II, which can deal with the non-dominated problem [32] well, is adopted in this paper. The main framework is shown in Figure 2.

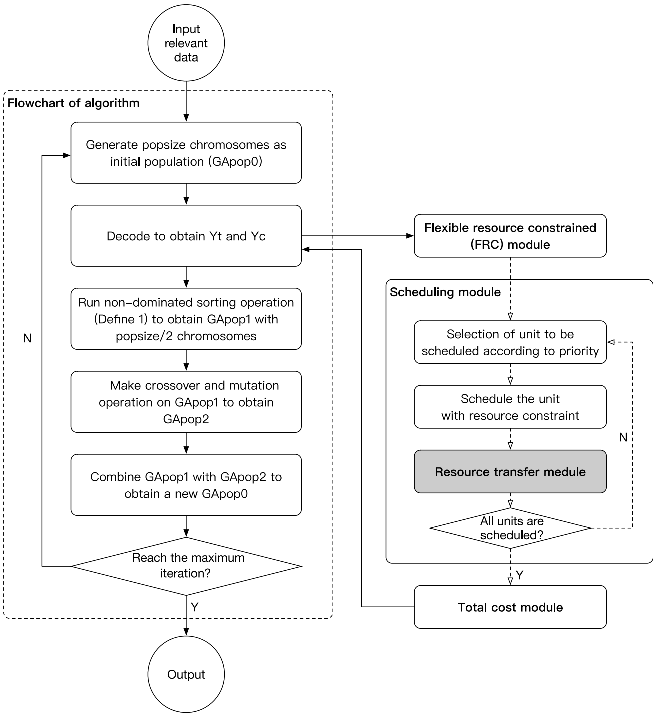

Figure 2. Algorithm framework

There are four core modules in this framework:

(1) **FRC module** - to deal with resource constraint floating in interval;

(2) **Scheduling module** - to schedule each unit without resource transfer;

(3) **Resource transfer module** - to allocate resources for transferring;

(4) **Total cost module** - to calculate the total project cost.

These four modules are used to decode chromosomes to complete the iteration of the algorithm.

2.1.1 FRC Module

In this paper, FRC module is developed to resolve resource conflicts caused by resource transfer. FRC means that the constraint of resource can float freely within a certain range. The algorithm is required to calculate the solution with the highest cost performance in the floating range of the constraint of resource. For a particular calculation, the current resource constraint has to be calculated based on floating values. Before starting the optimization algorithm, the constraint of various resource $(R_k^0 + R_k')$ shall be determined. R_k^0 is the initial constraint of the resource k in each time slot and is usually determined by the manager before scheduling. R_k' is the particular floating values and can be calculated by three parts. The formula is as follows:

$$R_k' = percent_k * L_k * R_{kstep}' \quad \textbf{(1)}$$

In the formula, $percent_k * L_k$ represents the step length of each float, L_k denotes the width/2 of the floating range of the resource constraint of resource k. R_{kstep}' denotes the amount of steps and is a random integer value in the range $[1/percent_k, 1/percent_k]$.

2.1.2 Scheduling Module

Scheduling module is presented to calculate schedule with minimal project duration which is consistent with the resource constraint and resource transfer scheme. In order to record the information of resource retention of units and resource transfer, we indroduce a resource retention matrix *RRM*. A matrix element $RRM_{ka_{ij}}\theta$ consists of several parts: resource k is occupied for a specified period of time θ by a_{ij}. The value of $RRM_{ka_{ij}}\theta$ represents the amount of resources occupied by a_{ij} during θ. These resources can only be transferred when the unit is completed. The resource pool is treated as a virtual unit a_p which does not need to schedule, but needs to calculate transfer of resources. All resources are initially transferred from the resource pool, and resource constraint is reflected in the initial amount of the resource pool.

Considering the status of units, three sets of units are established:

(1) A_1 : units for which scheduling has been completed.

(2) A_2 : units that are awaiting scheduling. The status of all immediate predecessor units is completed.

(3) A_3 : All units, with the exception of A_1 and A_2.

The specific calculation steps are as follows:

Step 1. Parameter initialization.

Step 2. Update A_1, A_2 and A_3. Check if A_2 is void. If void, go to step 7. Otherwise, the a_{ij} with maximum precedence in A_2 shall be identified for step 3.

Step 3. Schedule the a_{ij} with method of Hyari, et al. (2009) to obtain $ST_{a_{ij}}$ and $ET_{a_{ij}}$.

Step 4. Record the resource requirement of a_{ij} in *RRM*, that is $RRM_{ka_{ij}(ST_{a_{ij}}\ to\ ET_{a_{ij}})} = r_{a_{ij}m_{a_{ij}}k}$.

Step 5. Check whether the amount of all transferable resources can meet the resource requirement of a_{ij}. If not, $ST_{a_{ij}} = ST_{a_{ij}} + 1$ and $ET_{a_{ij}} = ET_{a_{ij}} + 1$, and check the amount of transferable resources again. Otherwise, sent the result to resource transfer module.

Step 6. After resource transfer module, *RRM* is to be updated. Suppose resources are transferred from a_{cv} to a_{ij}, $RRM_{ka_{cv}(ST_{a_{cv}}\ to\ ET_{a_{cv}})} = RRM_{ka_{cv}(ST_{a_{cv}}\ to\ ET_{a_{cv}})}$ and $RRM_{ka_{ij}(ST_{a_{ij}}\ to\ ET_{a_{ij}})}$ stays the same. Then repeat step 2.

Step 7. All units have been scheduled. The latest finish time of all units is the project duration (Y_t) of the current scheduling.

2.1.3 Resource Transfer Module

The time generated in the process of resource transfer is usually defined by the relative position between units, the quatity of resources and the type of resource [18]. It is necessary to study the resource transfer problem of repetitive projects, due to the long distance between units and the difficulty of transferring equipment or other resources. In reality, when a unit starts, it needs all resources in place that will be transferred from the resource pool or from one or more unit(s) which has previously completed. During the preliminary phase of the project, resources are prepared in the resource pool of the project, where the initial amount of resources in the pool is the maximum amount of available resource for the project. According to Mittal and Kanda (2009) [30], there is no idle time and cost for resource in the resource pool. This paper supposes that there are three manners for resource transfer.

1. The resources are to be transferred from the resource pool to units in different locations;
2. The resources are to be transferred among units with direct predecessors;
3. The resources are to be transferred among units without direct predecessors.

The transfer destination unit and the requirement of resource have been identified in step 4 of scheduling module. Problems of resource transfer module consist of: (1) find out resources source(s); (2) identify the amount of resources transferred from each source; (3) determine the changes of the schedule after transferring. Detailed steps as follows:

Step 1. Identify completed units or resource pool that still retain resources in *RRM.*

Step 2. Calculate the minimum start time of a_{ij} generated by the transfer of resources from sources, eg. each unit or pool, in *RRM.*

Step 2.1 If from completed unit a_{cv}, $ST_{a_{ij}}^{a_{cv}} = ET_{a_{cv}} + RTT_{v_j}$. $ST_{a_{ij}}^{a_{cv}}$ represents the adjusted start time of a_{ij} after accepting resources from a_{cv}; RTT_{vj} represents the time required to transfer resources from location *v* to *j*.

Step 2.2 If from resource pool a_p, $ST_{a_{ij}}^{a_p} = RTT_{p_j}$.

Step 3. Sort sources (unit or pool) by adjusted start time ($ST_{a_{ij}}^{a_{cv}}, \cdots, ST_{a_{ij}}^{a_p}$) from low to high, and transfer from source with lower adjusted start time.

Step 4. If the adjusted start time of multiple sources are the same, the selection in order of the transfer cost ($RTC_{a_{cv}a_{ij}}, \cdots, RTC_{a_p a_{ij}}$) of these sources from low to high.

Step 5. Until the transferred resources have met the resource demands of a_{ij}.

Setp 6. The $ST_{a_{ij}}$ will be changed to the maximal adjusted start time of all selected sources.

2.1.4 Total cost module

In DTCTP, the corresponding total cost (Y_c) needs to be calculated. In confirmation to Hyari, et al. (2009), Y_c consists of labor cost (LC), equipment cost (EC), material cost (MC), idle cost (IdleC), and indirect cost (IC). In this paper, we introduce two more cost: the flexible resource constraint cost (FRCC) and the resource transfer cost (RTC), and adjust the calculation of IdleC due to the resource transfer sheme. The basic description is as follows:

(1) The total cost (Y_c)

$$= LC + EC + MC + IdleC + IC + FRCC + RTC \quad \textbf{(2)}$$

The details of LC/EC/MC/IC can be found in Hyari, et al. (2009).

(2) The flexible resource constraint cost (FRCC)

Usually the scheduling will have a default resource constraint (R_k^0), and the actual resource constraint will float around R_k^0, each float will produce changes in management costs. When the actual resource constraint is less than R_k^0 ($R_k' < 0$), the management cost decreases; when $R_k' > 0$, it increases. This decreased or increased management cost is denoted as flexible resource constraint cost (FRCC). It is determined by the project duration, the amount of float steps and the daily cost per step of resource k ($FRCCr_k$).

$$= Y_t \times \sum_{k=1}^{K} (R'_{kstep} * FRCCr_k) \quad \textbf{(3)}$$

Formula (3) calculates the FRCC of resource k which incurred by the float of resource constraint.

(3) The resource transfer cost (RTC)

Few studies have been conducted on resource transfer costs (RTC). In Huang, et al. (2016), RTC is introduced for the first time, but it was regarded as fixed cost. In this paper, we present a calculable RTC, which is related to two factors: Resource transfer cost rate (RTCR) and the quantity of transferred resources (QTR). RTCR denotes cost for the transfer of unit resource from source to destination. As long as the type of resource and the relative position of each unit are determined, RTCR can be obtained by investigation beforehand. For example, if a large-scale equipment is to be transferred and one truck is needed for each transfer, RTCR of the equipment, consists of rent, road toll and fuel bills for one truck, can be obtained in advance through investigate. QTR can be obtained in resource transfer sheme. In addition, for different types of resource, QTR is expressed differently, such as the number of people and equipments, the volume of earthwork or even directly in terms of expenses. Once QTR is expressed in expenses, the RTCR may be expressed as a percent. The larger the QTR is, the larger the RTC generated. Suppose resources transferred from a_{cv} to a_{ij}, the RTC is calculated as:

$$RTC^k_{a_{cv}a_{ij}} = RTCT^k_{a_{cv}a_{ij}} * QTR^k_{a_{cv}a_{ij}} \quad (4)$$

$RTCR^k_{a_{cv}a_{ij}}$ and $QRT^k_{a_{cv}a_{ij}}$ represent the RTCR and QTR of resource k from a_{cv} to a_{ij} respectively.

(4) The idle cost (IdleC)

In previous studies [3, 14, 17], it is believed that idle cost will occur when resources cannot be continuously applied, and this cost only appears between adjacent units. This cost is defined as a function of the daily idle cost of the selected resource and the number of interrupted days (idle time) scheduled for that resource. In this paper, we have adjusted the calculation methods of both of them. (1) The daily idle cost of the selected resource is divided into two parts: the quatity of resources and the daily cost per unit of resource. We assume that the daily idle cost is not fixed, but increases with the increase of the quatity of idle resources. (2) we believe that the idle time is not limited to the adjacent units, but changes with the change of resource transfer path. We define unutilized resource as idle resource, so when the source and destination of resource transfer are determined, the interval period between the two units is the idle time (idleT). The transfer process of resources also calculates the idleT. Suppose resources transferred from a_{cv} to a_{ij}, the formula of IdleC is:

$$IdleC_{a_{cv}a_{ij}} = QTR^k_{a_{cv}a_{ij}} * RCD_k * IdleT_{a_{cv}a_{ij}} \quad (5)$$

$$IdleT_{a_{cv}a_{ij}} = ST_{a_{ij}} - ET_{a_{cv}} \quad (6)$$

RCD_k represents the daily cost per unit of resource k. If resources are transferred from the resource pool, $IdleT_{a_p a_{ij}} = RTT_{p_j}$.

2.2 Proposed Genetic Algorithm

This paper adopt NSGA-II, which is a bi-objective optimization genetic algorithm based on non-dominated ranking. The new model is developed for non-dominated problems helps in sorting of GA. The algorithm is composed of Initialization, Non-dominated sorting, Crossover operation and Mutation operation.

2.2.1 Initialization

The decision variable of the FRCDTCTP-rt problem in repetitive projects consists of: the execution mode ($m_{a_{ij}}$) and the order of precedence of units. $m_{a_{ij}}$ must be selected from the acceptable modes of M_i and correspond to a specific construction efficiency. The order of precedence determines the sequance of units and are composed of randomly generated consecutive numbers which can not repeat.

2.2.2 Non-dominated Sorting

Through the scheduling model, the corresponding Y_t and Y_c of each individual in Gapop0 can be achieved. A selection in GApop0 then needs to be made based on the level and crowding distance of Y_t and Y_c according to the non-dominated sorting operation.

(1) All individuals are allocated to the non-dominated level $F_{q_{rank}}$ according to the non-dominated rank (q_{rank}) of the individual.

(2) Sort the individuals of the same non-dominated level in ascending order of the objective values and calculate the corresponding crowding distance as follows:

$$\text{Crowding Distance} = \frac{f_{Y_t}(q+1) - f_{Y_t}(q-1)}{f^{\max}_{Y_t} - f^{\min}_{Y_t}} + \frac{f_{Y_c}(q+1) - f_{Y_c}(q-1)}{f^{\max}_{Y_c} - f^{\min}_{Y_c}} \quad (7)$$

f_{Y_t} and f_{Y_c} denote the objective function of the two objective Y_t and Y_c. Calculating the difference between two individual objective values adjacent to individual q in molecule. $f^{\max}$ and $f^{\min}$ denote the maximum value and minimal value, respectively, of the objective function of all individuals in the non-dominated level of individual q.

(3) When the levels and crowding distance of all individuals are obtained, select the appropriate individual from the binary tournament selection strategy for the genetic calculation of the next step. The specific condition consists of two parts, i.e., the lower levels or larger crowding distance of the same level.

2.2.3 Crossover Operation

Two chromosomes are randomly selected from GApop1 as parents. The crossover operation in this paper is run in two crossover modes. (1) The first crossover mode randomly selects the crossover points from the execution mode. Then, new offspring are generated by exchanging gene fragments after the crossover points between parents. (2) For the order of precedence, to avoid repetition, five gene loci are randomly selected from parent 1, which are subsequently exchanged with gene fragments of the corresponding loci in parent 2. Then, repeated parts are identified, in the fragments of the two parents and replaced with the previous part.

2.2.4 Mutation Operation

For execution mode, randomly select a point on the chromosome and select a different execution mode from M_i for replacement. For the precedence, randomly select two points on the chromosome and swap their positions.

3 First Example

3.1 Results

This section considers excavation construction of four bridges, which is consist of one activity (L = 1) and four units (N = 4), to clearly demonstrate the principle and practical significance of the model.

There is only one execution mode of each unit in this case, the duration and resource demands (number of drilling machines) of each unit are shown in Table 2. Each machine's daily cost is $100 (*RCD*=100). With the distance between units, for each additional unit, the RTT and RTCR increased by 1 day and $15. The location of resource pool coincides with that of a_B. It does not take time for resources to move from resource pool to a_B, and the time from resource pool to other units is the same as that from a_B. The indirect cost rate of the project is $150. The constraint of resource is five machines.

Table 2. Duration and Resource Demands of Each Unit

Unit (a_y)	Duration (d_{a_y}/d)	Resource demands (r_{a_y})
A	3	4
B	2	3
C	3	2
D	2	4

Suppose resources are transferred from a_z to a_y. Table 3 shows the resource requirement of the destination unit (r_{a_y}), the quatity of resource transfer ($QTR_{a_z a_y}$) and the cost for the transfer per unit resource ($RTCR_{a_z a_y}$), the sending and receiving time, and the time (RTT_{z_y}) and cost ($RTC_{a_z a_y}$) for a single transfer.

Table 3. Informations of Resource Transfer

a_z	a_y	Sent T	Recd T	r_{a_y}	$QTR_{a_z a_y}$	$RTCR_{a_z a_y}$	$RTC_{a_z a_y}$	RTT_{z_y}	$idleT_{a_z a_y}$
P	A	0	1	4	4	15	60	1	1
P	B	5	5	3	1	0	0	0	0
A	B	4	5		2	15	30	1	1
A	C	5	7	2	2	30	60	2	3
B	D	9	11	5	3	30	90	2	4
C	D	10	11		2	15	30	1	1

Taking the scheduling process of a_A and a_B as an example to introduce the application of resource transfer sheme, the detail is as follows:

Unit a_A : is scheduled through schedule module without considering resource transfer, $ST_{a_A}=0$, $ET_{a_A}=ST_{a_A}+d_{a_A}=3$. Four machines need to be transferred from resource pool (a_p) to meet the resource demands of a_A. The transfer time $RTT_{p_A}=1$, the transfer cost $RTC_{a_p a_a}=RTCR_{a_p a_a}*QTR_{a_p a_a}=15*4=60$.

Depending on the transfer time, the ST_{a_A} and ET_{a_A} need to be delayed by one day. The idle cost $idleC_{a_p a_A}=QTR_{a_p a_A}*RCD*RTT_{p_A}=4*100*1=400$.

Unit a_B : is also scheduled through schedule module firstly, $ST_{a_B}=4$, $ET_{a_B}=6$. Next, enter the resource transfer module. There are two possible sources, a_p or a_A.

Calculate the transfer time separately − from a_p, $RTT_{p_B}=0$, $ST_{a_B}^{a_p}=ST_{a_B}+RTT_{p_B}=4$; from a_A, $RTT_{AB}=1$, $RTT_{a_B}^{a_A}=5$;

Determine the source unit − Due to $ST_{a_B}^{a_p}<ST_{a_B}^{a_A}$, priority should be given to transferring resources from a_p, and the inadequate part will be supplemented from

a_A. The $ST_{a_B} = \max(ST_{a_B}^{a_p}, ST_{a_B}^{a_A}) = 5, ET_{a_B} = 7.$

Calculation the RTC and $IdleC$ – In view of $r_{a_B} = 3$, one machine is transferred from a_p and two from a_A.

One from a_p, $RTC_{a_p a_B} = 0*1 = 0$, $IdleC_{a_p a_B} = 1*100 = 0 = 0$;

Two from a_A, $RTC_{a_A a_B} = 15*2 = 30$, $IdleT_{a_A a_B} = ST_{a_B} - ET_{a_A} = 1$, $IdleC_{a_A a_B} = QTR_{a_p a_B} * RCD * IdleT_{a_A a_B} = 2*100*1 = 200$.

Final result: can be obtained as Y_t=13 and Y_c=8120, and the schedule of all units is shown in Figure 3.

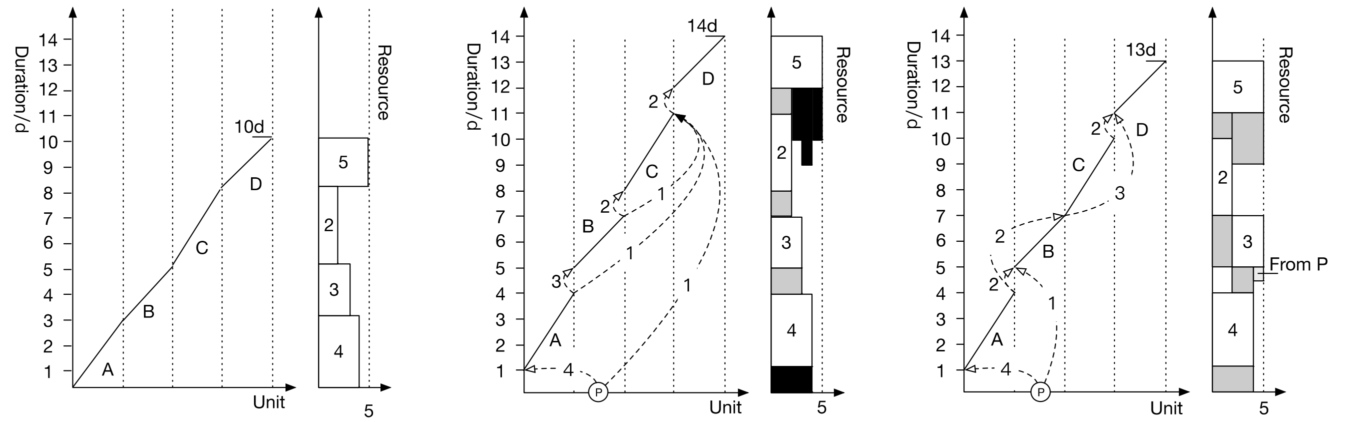

Figure 3. Final schedules of case study

3.2 Discussion

Figure 3 shows the comparision of the research results. Figure 3(a) shows the scheme based on the method of Hyari, et al. (2009) (regardless of resource transfer). Although its construction period can be optimized, it usually results in delays or cost increases in the actual construction process due to the failure to consider the resource transfer process in the plan. Figure 3(b) shows the scheme obtained according to the method of Huang, et al. (2016), which is closer to reality than Hyari. However, the construction requirements of units cannot usually be met in this method, due to only the transfer of resources between adjacent units is considered. For instance, the light-colored part in resource coordinate map is the process of resource transfer based on Huang's method. Due to $r_{a_D} > r_{a_C}$, the quatity of resources transferred from a_C can not satisfy the demands of a_D. Some resources need to be transferred from $a_p / a_A / a_B$ respectively, shown as the dark part. The final result is $Y_t = 14$ and $Y_c = 8770$. As can be seen from the comparison in Figure 3(c), the method in this paper not only takes into account the different resource requirements of all units, but also effectively reduces the total duration and cost by transferring resources in advance. Compared with Huang, Y_t is reduced by 1d and Y_c is reduced by \$650.

4 Second Example

4.1 Results

Resource conflicts become more intense with resource transfer, then resource constraint have greater impact on scheduling schemes. Managers usually choose to adjust resource constraint to obtain multiple feasible solutions for comparison. It is generally believed that increasing the constraint of resource will increase the cost while shortening the duration, and reducing the constraint of resource will lead to the opposite result. This situation, such as a seesaw, is only applicable to the single optimal solution. However, in FRCDTCTP-rt, by adjusting resource constraint, a better set of solutions can be obtained, rather than a single solution.

An extensively researched bridge construction project example [3, 14] will be used in this paper to verify this opinion. According to Hyari, et al. (2009), the minimum duration without resource constraint of this project is 107d. In the example, L=5 and N=4. The main activities are excavation, foundation, column, beam and slab. Among them, excavation, foundation and column belong to block/bar activity, while beam and slab belong to lines activity. In this paper, only the resource transfer among units of block/bar activity is considered. The default is that the resources between units of lines activity move continuously, and there is no resource transfer cost.

For the workload, acceptable construction modes and other relevant data, please refer to Table 4.

Table 4. Project Data for a Concrete Bridge

Activity (i)	Excavation (i=1)				Foundation (i=2)				Column(i=3)			
Unit (j)	1	2	3	4	1	2	3	4	1	2	3	4
Quantity of work (m^3)	1,147	1,434	994	1,529	1,032	1,077	943	898	104	86	129	100
Mode (M_i)	1				1	2	3		1	2	3	
Productivity (m^3/d)	91.75				89.77	71.81	53.86		5.73	6.88	8.03	
Labor cost ($/d)	340				3,804	2,853	1,902		1,875	2,438	3,000	
Equipment cost ($/d)	566				874	655	436		285	371	456	
Material cost ($/d)	0				92				479			
Activity (i)	Beam(i=4)				Slab(i=5)							
Unit (j)	1	2	3	4	1	2	3	4				
Quantity of work (m^3)	85	92	101	80	0	138	114	145				
Mode (M_i)	1	2	3	4	1	2						
Productivity (m^3/d)	9.9	8.49	7.07	5.66	8.73	7.76						
Labor cost ($/d)	3,931	3,238	2,544	1,850	2,230	1,878						
Equipment cost ($/d)	315	259	204	148	177	149						
Material cost ($/d)	195				186							

Since two types of renewable resource exist for this instance, only the labor cost constraint is considered to reduce the complexity. The daily indirect cost of the project is $2,500/d and the daily cost per step of the floating fo resource constraint is $300 ($FRCCr_{LCR}=300$). The transfer times and transfer cost rate are showed in Table 5 as [RTT(d) / RTCR(%)].

Table 5. RTT and RTCR

Location	j=1	j=2	j=3	j=4	j=p
j=1	[0/0]	[1/0.1]	[2/0.15]	[3/0.2]	[1/0.1]
j=2	[1/0.1]	[0/0]	[1/0.1]	[2/0.15]	[0/0]
j=3	[2/0.15]	[1/0.1]	[0/0]	[1/0.1]	[1/0.1]
j=4	[3/0.2]	[2/0.15]	[1/0.1]	[0/0]	[2/0.15]
j=p	[1/0.1]	[0/0]	[1/1]	[2/0.15]	[0/0]

This paper solves the project in three cases:

Case1: obtain solution set by DTCTP-rt with fixed resource constraint. The amount of resource constraint is $15020 (R^0_{LCR} =15020), which is the maximum resource demands result without considering resource transfer and resource constraint in Hyari, et al. (2009).

Case2: obtain solution set by method of Huang, et al. (2016) with fixed resource constraint too. The amount of resource constraint is the same as case1.

Case3: obtain solution set by FREDTCTP-rt, that the resource constraint floats within a certain range. The initial resource constraint (R^0_{LCR}) is the same as case1. The final resource constraint floats up and down within an interval of no more than 30%* R^0_{LCR} ($L_k=R^0_{LCR}$ * 30%). At this point, the floating step length of the resource constraint is set to L_{LCR}/3= R^0_{LCR} *10%=1502 ($percent_{LCR}$=1/3). So the resource constraint of case3 floats in the interval [$R^0_{LCR}-R^0_{LCR}$, $R^0_{LCR}+L_{LCR}$]= [10514, 19526] with step length 1502. In line with $percent_{LCR}$, the amount of steps ($R'_{LCRstep}$) can only take integers between [-3, 3]. For example, when $R'_{LCRstep}$ =1, resource constraint is $R^0_{LCR}+R'_{LCR}$ = R^0_{LCR} + R^0_{LCR} =*10%*1=16522.

4.2 Discussion

The data comparison of the three cases is shown in the Figure 4. The differences between DTCTP-rt and Huang's method is described in detail in illustrative example 1. By comparing case1 and case2 in Figure 4, we can see the difference in solution quality between them. The results of case1 are mostly concentrated in the lower left of case2, which shows that DTCTP-rt's results are better in terms of duration and cost. Especially the shortening of project duration is very obvious. The minimum duration of case1 is 110d, which is 6 days less than case2.

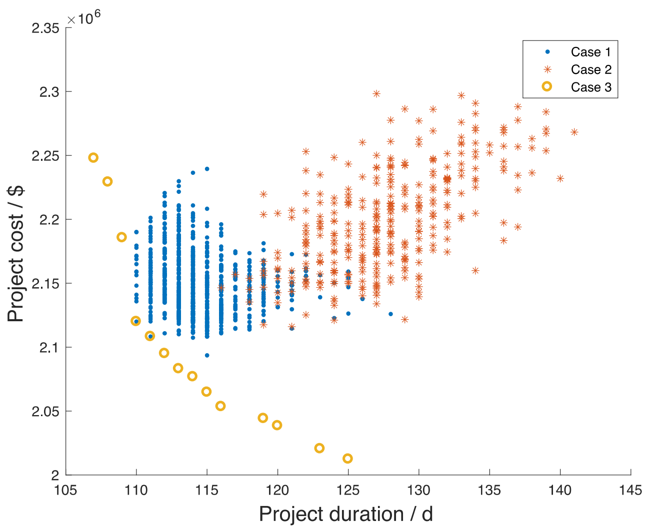

Figure 4. Comparison of results

The results of case 3 are shown in Table 6. It can be seen that, through comparing each result, with the reduce of resource constraint ($R'_{LCRstep}$), the duration of the project (Y_t) is increasing, while the cost (Y_c) is decreasing. This fits the initial assumption about the impact of changes in resource constraint.

Table 6. The Solutions of FRCDTCTP-rt

Project Duration (Y_t)	Project Cost (Y_c)	$R'_{LCRstep}$
107	2,247,733	3
108	2,229,094	2
109	2,185,536	1
110	2,119,977	0
111	2,108,286	0
112	2,094,939	-1
113	2,083,048	-1
114	2,076,833	-1
115	2,064,701	-2
116	2,053,459	-2
119	2,044,108	-3
120	2,038,476	-2
123	2,020,488	-3
125	2,012,360	-3

However, this is to think from the perspective of a single result. Unlike the traditional way of thinking, we do not compare the advantages and disadvantages of one single solution, but from the perspective of the whole solution set, due to this is more in line with the needs of actual management. In practice, managers'goals are usually less clear than the optimization objectives, such as minimum duration or minimum cost. Most of the cases are based on the comparison of multiple schemes to make decisions, so it is more practical to provide multiple better feasible options for reference. By comparing the results, we can find that the most solutions of case3 is better than case1.

We can see that FRCDTCTP-rt can (1) obtain solutions with lower project duration by increasing resource constraint, e.g. the solutions with $Y_t = 107$, 108 and 109; (2) get a lower cost solution, under the same duraion, e.g. the solutions with $Y_t = 112$ to 125; (3) and with the increase of the project duration, the difference of the cost between two methods is more obvious. There may be a cost gap over $100,000 under the same Y_t in this example, e.g. at $Y_t = 125$, the minimum cost of these two methods are respectively $2,126,265 in case 1 and $2,012,360 in case 3.

5 Conclusions

In this paper, a scheduling model considering the cost of resource transfer and the flexible change of resource supply is proposed.

First, FRC module processes flexible resource supply to find Pareto optimal solution of global time and cost from different resource supply intervals. Pareto optimality a situation where no preference or individual criterion can be better off without creating at least single preference or individual criterion. Secondly, Scheduling module pre-schedules each unit to generate scheduling schemes that do not consider resource transfer time to determine new resource demand and demand time. Thirdly, resource transfer module chooses the best resource transfer supply unit and determines the resource transfer route according to the resource demand of the current unit, the resource retention of the preceding unit and the time and cost of resource transfer among the units. Fourth, total cost module will calculate the total project cost including the cost of resource transfer and the cost of resource supply change.

Two examples are given to illustrate the application of the model and its original contribution. The main contribution of this research is to introduce the concept of flexible resource supply and optimize the existing resource transfer modes of non-linear projects and block/bar activities, taking into account the cost of resource transfer. This improvement can make the model scheduling results more in line with the actual needs, so that managers can (1) accurately judge the impact of resource transfer process on scheduling results in repetitive projects with large mileage span; (2) get better scheduling results with better time and cost through adjusting the supply of resources.

References

[1] M. A. Ammar, LOB and CPM Integrated Method for Scheduling Repetitive Projects, *Journal of Construction Engineering & Management*, Vol. 139, No. 1, pp. 44-50, January, 2013.

[2] X. Zou, L. Zhang, Q. Zhang, A Biobjective Optimization Model for Deadline Satisfaction in Line-of-Balance Scheduling with Work Interruptions Consideration, *Mathematical Problems in Engineering*, Vol. 2018, Article ID 6534021, May, 2018.

[3] K. H. Hyari, K. El-Rayes, M. El-Mashaleh, Automated trade-off between time and cost in planning repetitive construction projects, *Construction Management & Economics*, Vol. 27, No. 8, pp. 749-761, August, 2009.

[4] X. Zou, S. C. Fang, Y. S. Huang, L. H. Zhang, Mixed-Integer Linear Programming Approach for Scheduling Repetitive Projects with Time-Cost Trade-Off Consideration, *Journal of Computing in Civil Engineering*, Vol. 31, No. 3, pp. 06016003.1- 06016003-6, May, 2017.

[5] A. Altuwaim, K. El-Rayes, Minimizing duration and crew work interruptions of repetitive construction projects, *Automation in Construction*, Vol. 88, pp. 59-72, April, 2018.

[6] D. H. Tran, J. S. Chou, D. L. Luong, Multi-objective symbiotic organisms optimization for making time-cost tradeoffs in repetitive project scheduling problem, *Journal of Civil Engineering and Management*, Vol. 25, No. 4, pp. 322-339, April, 2019.

[7] P. Ghoddousi, E. Eshtehardian, S. Jooybanpour, A. Javanmardi, Multi-mode resource-constrained discrete time–cost-resource optimization in project scheduling using non-dominated

sorting genetic algorithm, *Automation in Construction*, Vol. 30, pp. 216-227, March, 2013.

[8] J. D. García-Nieves, J. L. Ponz-Tienda, A. Salcedo-Bernal, E. Pellicer, The Multimode Resource-Constrained Project Scheduling Problem for Repetitive Activities in Construction Projects, *Computer-Aided Civil and Infrastructure Engineering*, Vol. 33, No. 8, pp. 655-671, August, 2018.

[9] G. Heravi, S. Moridi, Resource-Constrained Time-Cost Tradeoff for Repetitive Construction Projects, *KSCE Journal of Civil Engineering*, Vol. 23, No. 8, pp. 3265-3274, August, 2019.

[10] L. H. Zhang, Y. P. Tang, J. X. Qi, Resource Leveling Based on Backward Controlling Activity in Line of Balance, *Mathematical Problems in Engineering*, Vol. 2017, Article ID 7545980, February, 2017.

[11] Y. J. Tang, Q. X. Sun, R. K. Liu, F. T. Wang, Resource Leveling Based on Line of Balance and Constraint Programming, *Computer-Aided Civil and Infrastructure Engineering*, Vol. 33, No. 10, pp. 864-884, October, 2018.

[12] S. L. Fan, K. S. Sun, Y. R. Wang, GA optimization model for repetitive projects with soft logic, *Automation in Construction*, Vol. 21, pp. 253-261, January, 2012.

[13] L. Zhang, X. Zou, J. Qi, A trade-off between time and cost in scheduling repetitive construction projects, *Journal of Industrial & Management Optimization*, Vol. 11, No. 4, pp. 1423-1434, October, 2015.

[14] Y. S. Huang, X. Zou, L. H. Zhang, Genetic Algorithm–Based Method for the Deadline Problem in Repetitive Construction Projects Considering Soft Logic, *Journal of Management in Engineering*, Vol. 32, No. 4, pp. 04016002.1- 04016002.9, July, 2016.

[15] J. L. Ponz-Tienda, E. Pellicer, J. Benlloch-Marco, C. Andr´es-Romano, The Fuzzy Project Scheduling Problem with Minimal Generalized Precedence Relations, *Computer-aided Civil & Infrastructure Engineering*, Vol. 30, No. 11, pp. 872-891, November, 2015.

[16] T. Salama, O. Moselhi, Multi-objective optimization for repetitive scheduling under uncertainty, *Engineering, Construction & Architectural Management*, Vol. 26, No. 7, pp. 1294-1320, May, 2019.

[17] A. Altuwaim, K. El-Rayes, Optimizing the Scheduling of Repetitive Construction to Minimize Interruption Cost, *Journal of Construction Engineering & Management*, Vol. 144 No. 7, pp. 04018051.1-04018051.12, July, 2018.

[18] D. Krüger, A. Scholl, Managing and modelling general resource transfers in (multi-)project scheduling, *Or Spectrum*, Vol. 32, No. 2, pp. 369-394, April, 2010.

[19] P. G. Ioannou, I. T. Yang, Repetitive Scheduling Method: Requirements, Modeling, and Implementation, *Journal of Construction Engineering & Management*, Vol. 142, No. 5, pp. 04016002.1-04016002.13, May, 2016.

[20] M. C. Vorster, Y. J. Beliveau, T. Bafna, Linear scheduling and visualization, *Transportation Research Record*, No. 1351, pp. 32-39, January, 1992.

[21] K. K. Yang, C. C. Sum, A comparison of resource allocation and activity scheduling rules in a dynamic multi-project environment, *Journal of Operations Management*, Vol. 11, No. 2, pp. 207-218, June, 1993.

[22] K. K. Yang, C. C. Sum, An evaluation of due date, resource allocation, project release, and activity scheduling rules in a multiproject environment, *European Journal of Operational Research*, Vol. 103, No. 1, pp. 139-154, November, 1997.

[23] B. Afshar-Nadjafi, M. Majlesi, Resource constrained project scheduling problem with setup times after preemptive processes, *Computers & Chemical Engineering*, Vol. 69, pp. 16-25, October, 2014.

[24] D. Krüger, A. Scholl, A heuristic solution framework for the resource constrained (multi-)project scheduling problem with sequence-dependent transfer times, *European Journal of Operational Research*, Vol. 197, No. 2, pp. 492-508, September, 2009.

[25] S. Adhau, M. L. Mittal, A. Mittal, A multi-agent system for decentralized multi-project scheduling with resource transfers, *International Journal of Production Economics*, Vol. 146, No. 2, pp. 646-661, December, 2013.

[26] M. Suresh, P. Dutta, K. Jain, Resource constrained multi-project scheduling problem with resource transfer times, *Asia-Pacific Journal of Operational Research*, Vol. 32, No. 6, pp. 1550048.1-1550048.30, December, 2015.

[27] J. Poppenborg, S. Knust, A flow-based tabu search algorithm for the RCPSP with transfer times, *Or Spectrum*, Vol. 38, No. 2, pp. 305-334, March, 2016.

[28] M. Rostami, M. Bagherpour, M. M. Mazdeh, A. Makui, Resource Pool Location for Periodic Services in Decentralized Multi-Project Scheduling Problems, J*ournal of Computing in Civil Engineering*, Vol. 31, No. 5, pp. 04017022.1-04017022.16, September, 2017.

[29] J. Liu, M. Lu, Robust Dual-Level Optimization Framework for Resource-Constrained Multiproject Scheduling for a Prefabrication Facility in Construction, *Journal of Computing in Civil Engineering*, Vol. 33, No. 2, pp. 04018067.1-04018067.15, March, 2019.

[30] M. L. Mittal, A. Kanda, Scheduling of multiple projects with resource transfers, *International Journal of Mathematics in Operational Research*, Vol. 1, No. 3, pp. 303-325, April, 2009.

[31] P. Gustavsson, A. Syberfeldt, A New Algorithm Using the Non-dominated Tree to improve Non-dominated Sorting, *Evolutionary Computation*, Vol. 26, No. 1, pp. 89-116, March, 2018.

[32] G. Valentini, C. J. B. Abbas, L. J. G. Villalba, L. Astorga, Dynamic multi-objective routing algorithm: a multi-objective routing algorithm for the simple hybrid routing protocol on wireless sensor networks, *IET Communications*, Vol. 4, No. 14, pp. 1732-1741, September, 2010.

Biographies

Haobo Zou is currently a Ph.D. Candidate for economics and management of Southwest Jiao Tong University. His research interests are in the areas of project scheduling, operational research.

Guohua Zhou received the Ph.D degree in Management from School of economics and management of Southwest Jiao Tong University in 1991. He is currently a professor in Southwest Jiao Tong University. His research interests include: (1) Large complex project and multi project management, (2) Rail transit project decision and management, (3) Transportation logistics planning and strategic management.