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TIME-COST OPTIMIZATION MODEL FOR DETERMINISTIC NETWORK PROJECTS[1]

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Abstract: *A deterministic PERT activity-on-arc network* $G(N,A)$ *with logical operation "AND" at the event's receiver and "MUST FOLLOW" at the event's emitter, is considered. Each activity* $(i,j)\in A$ *entering the model can be operated within several deterministic durations* t_{ij} *depending on the corresponding budgets* c_{ij} *assigned to that activity. The problem centers on determining optimal budget values* c_{ij} *to be assigned to each activity* $(i,j)\in A$ *in order to minimize the network's critical path subject to the restricted pregiven budget* C *assigned to the whole project* $G(N,A)$.

Key words: *Deterministic PERT project; Restricted pregiven budget assigned to the project Optimal local budgets assigned to project's activities; Heuristic iterative algorithm; Critical path's minimization*

1. Introduction

A variety of publications (see Arisawa and Elmaghraby [1][7], Arsham [2], Ben-Yair [3], Deckro and Herbert [4], Golenko-Ginzburg [6-8], Howard [9], Kelley [10], Laslo [11-12], Panagiotakopoulas [13], Siemens [14], etc.) is related to stochastic network projects (in the form of a graph $G(N,A)$ comprising nodes $i \in N$ and activities $(i,j) \subset A$ leaving node i and entering node j) with random activity durations. For any activity (i,j) entering the network project $G(N,A)$, it is assumed that:

- the corresponding activity duration t_{ij} depends parametrically on the budget c_{ij} assigned to that activity, and
- the budget value c_{ij} satisfies

$$c_{ij\ min} \le c_{ij} \le c_{ij\ max},$$

where $c_{ij\ min}$ stands for the minimal budget capable of operating activity (i,j), and $c_{ij\ max}$ is the maximal budget required to operate activity (i,j). Both values $c_{ij\ min}$ and $c_{ij\ max}$ are pregiven beforehand.

Note that in case $c_{ij} > c_{ij\ max}$ additional value $c_{ij} - c_{ij\ max}$ is redundant. Thus, function $t_{ij} = f_{ij}(c_{ij})$ can be implemented for any $(i,j) \in A \subset G(N,A)$. The main objective of the time – cost trade-off procedure is to consider the relationship between the project duration and the total project costs.

The main purpose of the time – cost trade-off can be stated as the development of the procedure to determine activity cost assignments to reduce as much as possible the project duration time under restricted total project's costs (usually pregiven). The classical time – cost model is as follows:

Given a PERT graph $G(N,A)$ together with functions $t_{ij} = f_{ij}(c_{ij})$, $(i,j) \in G(N,A)$, and values $c_{ij\ min}$ and $c_{ij\ max}$, determine:

- the minimal total project direct costs C,

$$Min\ C, \qquad \text{and} \tag{1}$$

- the optimal assigned budget values c_{ij}^{opt}, subject to

$$T_{cr}\left\{t_{ij} = f_{ij}\left(c_{ij}^{opt}\right)\right\} \le D, \tag{2}$$

$$\sum_{\{i,j\}} c_{ij}^{opt} = C \,, \tag{3}$$

$$c_{ij\ min} \le c_{ij}^{opt} \le c_{ij\ max} \,, \tag{4}$$

where D stands for a pregiven due date.

Problem (1-4) is usually solved [4] by means of heuristic methods. In cases of non-linear f_{ij} the problem becomes too difficult to be solved analytically [1].

In [3, 7] the trade-off model minimizes the allocated budget under given time chance constraint. The extension of problem (1-4) for a random activity duration t_{ij} is as follows:

Given the PERT-COST project $G(N,A)$ with random activity durations t_{ij}, $(i,j) \in G(N,A)$, where for each activity (i,j) its probability density function (p.d.f.) $p_{ij}(t)$ depends parametrically on the budget c_{ij} assigned to that activity: the problem is to minimize the project's budget C

$$Min\ C \,, \tag{5}$$

as well as to determine the optimal budget volumes c_{ij}^{opt} assigned to each activity $(i,j) \in G(N,A)$ subject to

$$Pr\left\{ T\left[t_{ij} / c_{ij}^{opt} \right] \le D \right\} \ge p \,, \tag{6}$$

$$\sum c_{ij}^{opt} \le C \,, \tag{7}$$

$$c_{ij\ min} \le c_{ij}^{opt} \le c_{ij\ max} \,. \tag{8}$$

Here:

- $T\left[t_{ij} / c_{ij}^{opt} \right]$ stands for the project's random duration on condition that all the activity's durations are random values with p.d.f. $p_{ij}\left(t/c_{ij}\right)$. Value $T\left[t_{ij} / c_{ij}^{opt} \right]$ can be determined either via simulation, or by means of approximate analytical methods;
- D designates the pregiven due date;

- p is the minimal value of the chance constraint (pregiven by the project management as well).

Problem (5-8) is a very complicated problem which even for medium-scale projects cannot be solved analytically. It requires therefore heuristic solutions that are widely used nowadays in various design offices [7].

It can be well-recognized that even nowadays there do not exist both simple and effective time – cost optimization procedures. Moreover, even for most simplified deterministic activity-on-arc PERT networks where each activity can be operated with several rates by assigning several corresponding cost values for each activity, classical time – cost problems have not found as yet their solution. This refers both to minimizing the project's critical path duration by optimal allocation of the restricted project's budget among the activities, or to minimizing project's budget subject to the restricted critical path duration.

In this study we suggest a simple heuristic procedure which enables to solve both of the outlined above problems. An activity-on-arc network with logical operation "AND" at the event's receiver and "MUST FOLLOW" at the event's emitter, is considered. Each activity $(i, j) \in A$ entering the network can be operated by n_{ij} different rates, i.e., within n_{ij} different deterministic durations t_{ij} depending on n_{ij} corresponding budget values c_{ij} assigned to that activity. Both the direct and dual problems center on determining the optimal budget assignment c_{ij} among all activities (i, j) in order either to minimize the critical path duration subject to restricted project's total budget (direct problem), or to minimize the total budget subject to restricted (from below) critical path length.

The problems are solved by means of a simple heuristic procedure based on numerous critical path length calculations together with determining the so-called critical activity rates for each activity entering the project. The general idea is to diminish as much as possible the budget values assigned to activities with law critical rates, and to transfer the released budget for activities with high critical rates.

A numerical example is presented.

2. Definitions

In order to proceed we require the following definitions:

Definition 1. Call a PERT type deterministic network model properly enumerated if for any activity (i, j) entering the network relation $i < j$ holds.

Definition 2. Call a list of activities entering a properly enumerated network a lexicographically ordered list if *any* two different activities (i_1, j_1), (i_2, j_2) are placed in the list according to the following rules:

- if $i_1 < i_2$, (i_1, j_1) is placed before (i_2, j_2);
- if $i_1 = i_2$, and $j_1 < j_2$, (i_1, j_1) is placed before (i_2, j_2);
- in all other cases (i_1, j_1) is placed after (i_2, j_2).

Definition 3. For each activity (i, j) entering a PERT type deterministic network model, its critical activity rate CAR_{ij} can be calculated as follows [6]:

$$CAR_{ij} = 1 - \frac{T_{(j)}^{l} - T_{(i)}^{e} - t_{ij}}{T_{cr} - T^{*}\left[L_{cr}, L(i,j)_{\max}\right]}, \tag{9}$$

where:

- $T_{(j)}^{l}$ is the latest possible moment for event j to occur;
- $T_{(i)}^{e}$ is the earliest possible moment for event i to occur;
- $T\left[L(i,j)_{\max}\right]$ is the duration of the longest path connecting the source and the sink nodes and comprising activity (i, j);
- T_{cr} is the duration of the critical path L_{cr};
- $T^{*}\left[L_{cr}, L(i,j)_{\max}\right]$ is the duration of the part of $L(i,j)_{\max}$ which belongs to the critical path as well.

Note that for all activities (i, j) belonging to the critical path, relation $CAR_{ij} = 1$ holds.

3. Notation

Let us introduce the following terms:

$G(N, A)$	- deterministic PERT type network project;
$(i, j) \in A$	- activity leaving node i and entering node j;
M	- number of activities entering the project;
$t_{ij}(c_{ij})$	- deterministic activity duration depending on the budget value c_{ij} assigned to (i, j);
n_{ij}	- number of different budget values which can be assigned to (i, j);
c_{ijk}	- k-th budget value which can be assigned to (i, j), $1 \le k \le n_{ij}$ (pregiven); values c_{ijk} are given in ascending order;
t_{ijk}	- deterministic activity duration corresponding to value c_{ijk} (pregiven); it can be well-recognized that values t_{ijk} are given in descending order);
L_{cr}	- critical path of network $G(N, A)$;
$L(i,j)_{\max}$	- the longest path connecting the source and the sink nodes and comprising activity (i, j);

$T_{cr}/\{c_{ij}\}$ - critical path length obtained on the basis of duration $t_{ij}(c_{ij})$;

$T^{l}_{(j)}$ - the latest possible moment for event $j \in N \subset G(N,A)$ to occur;

$T^{e}_{(i)}$ - the earliest possible moment for event $i \in N \subset G(N,A)$ to occur;

$T^{*}[L_{cr}, L(i,j)_{\max}]$ - duration of the intersection between L_{cr} and $L(i,j)_{\max}$.

ΔC - cost value step (pregiven);

δT - relative accuracy value to obtain a quasi-optimal solution (pregiven);

ω - iterative relative change;

C - total budget value assigned to project $G(N,A)$ (pregiven).

Note that relation

$$\sum_{\{i,j\}} c_{ij1} \le C \tag{10}$$

holds, otherwise the problem has no solution.

In case

$$\sum_{\{i,j\}} c_{ijn_{ij}} \le C \tag{11}$$

the problem obtains a trivial solution $\{c_{ijn_{ij}}\}$.

4. The problem

The problem is to determine for each activity (i,j) entering the project, quasi-optimal values $c_{ij\varepsilon_{ij}}$, $1 \le \varepsilon_{ij} \le n_{ij}$, in order to minimize the project's critical path length subject to the pregiven project's budget:

$$\underset{\{c_{ij\varepsilon_{ij}}\}}{Min} \left\{T_{cr}/\{c_{ij\varepsilon_{ij}}\}\right\} \tag{12}$$

subject to

$$\sum_{\{i,j\}} c_{ij\varepsilon_{ij}} \le C. \tag{13}$$

Note that to determine an optimal combination of values $c_{ij\varepsilon_{ij}}$ by means of an analytical lookover algorithm leads even for small- and medium-size projects ($M < 15 \div 20$, $n_{ij} \approx 3 \div 5$) to enormous computational efforts. This is why preference has to be given to more attractive and at the same time more realistic heuristic algorithms. The latter result in obtaining quasi-optimal values which usually meet most practical requirements.

5. Heuristic algorithm

We will apply a newly modified version of the model outlined in [4, 7]. The step-wise procedure of the algorithm is as follows:

Step 1. Enumerate properly all the activities entering the project.

Step 2. Order lexicographically the list of activities.

It can be well-recognized that *Steps 1-2* appear in most textbooks on project management, e.g. in [6].

Step 3. By any means reassign budget C among the project's activities $(i, j) \in A \subset G(N, A)$ subject to

$$\sum_{\{i,j\}} c_{ij} = C \tag{14}$$

to obtain a feasible solution of the problem. One may suggest a variety of different methods to carry out *Step* 3 on the basis of (10), e.g. first to set c_{ij1} for each activity (i, j), and afterwards to reallocate the remainder $C - \sum_{\{i,j\}} c_{ij1} = \Re$ among the activities. This can be carried out by consecutively adding value ΔC to all activities (being arranged in an lexicographical order) by honouring their maximal possible values $c_{ijn_{ij}}$, until the remainder $\Re$ will be totally exhausted.

Step 4. Calculate the project's critical path length T_{cr} for values c_{ij} and durations t_{ij} obtained on *Step* 3. Call the obtained value $T_{cr}^{(1)}$.

Step 5. Calculate by means of (9) the activities' CAR_{ij} values.

Step 6. Reorder the project's activities in descending order of their CAR_{ij} values. For (i, j) with similar CAR values place first activities with smaller lexicographical numbers.

Step 7. Choose the activity with the minimal CAR_{ij} value (i.e., in the right part of the list), on condition that its budget value c_{ij} may be decreased by value $\Delta_1 = c_{ij} - c_{ij1} \geq \Delta C$ in order not to exceed the threshold level c_{ij1}. Call that activity $\left(i_\eta, j_\eta\right)$.

Step 8. Choose the activity with the maximal CAR_{ij} value (in the left part of the list), on condition that its budget value c_{ij} may be increased by value $\Delta_2 = c_{ijn_{ij}} - c_{ij} \geq \Delta C$ in order not to exceed limit $c_{ijn_{ij}}$. Call that activity $\left(i_\gamma, j_\gamma\right)$.

Step 9. Transfer cost value $Z = \min\left(\Delta_1, \Delta_2\right)$ from $\left(i_\eta, j_\eta\right)$ to $\left(i_\gamma, j_\gamma\right)$. Calculate

$C_{i_\eta j_\eta} - Z \Rightarrow C_{i_\eta j_\eta}$,

$C_{i_\gamma j_\gamma} + Z \Rightarrow C_{i_\gamma j_\gamma}$.

Step 10. Check inequality $C_{i_\eta j_\eta} > C_{i_\eta j_\eta 1}$. If inequality holds, calculate $C_{i_\eta j_\eta} - C_{i_\eta j_\eta 1} = \Delta_1$ and go to *Step 8*. In case $C_{i_\eta j_\eta} = C_{i_\eta j_\eta 1}$, i.e., $\Delta_1 = 0$, apply the next step.

Step 11. Calculate new values t_{ij} for all activities entering the project.

Step 12. Calculate value T_{cr} on the basis of *Step 11*. Call this value $T_{cr}^{(2)}$.

Step 13. Calculate the iterative change

$$\omega = \frac{T_{cr}^{(1)} - T_{cr}^{(2)}}{T_{cr}^{(1)}} \qquad (15)$$

to compare the latter with the relative accuracy δT.

Step 14. If $\omega > \delta T$, apply the next step. Otherwise go to *Step 16*.

Step 15. Set $T_{cr}^{(2)} \Rightarrow T_{cr}^{(1)}$. Go to *Step 5*.

Step 16. The heuristic algorithm terminates. Value $T_{cr}^{(2)}$ obtained at *Step 12*, set $\left\{c_{ij}\right\}$ determined at *Step 9* as well as values $\left\{t_{ij}\right\}$ calculated at *Step 11* are taken as quasi-optimal values of the problem's solution.

It can be well-recognized that the general idea of *Steps 7-10* is to diminish the assigned budget for activity $\left(i_\eta, j_\eta\right)$ with the minimal CAR to its minimal value $C_{i_\eta j_\eta 1}$ in order to reassign the gained reserve value Δ_1 among activities with higher CAR values. Note that the number of those activities may be more than one.

In certain cases *Step 9* may be simplified by substituting value Z for value ΔC. Although such a substitution increases the number of iterations, it simplifies the solution procedure and refines the algorithm's accuracy.

The outlined above algorithm solves the direct time-cost optimization problem (12-13). As to the dual time-cost problem with pregiven project duration D

$$Min\ C \tag{16}$$

subject to

$$T_{cr} \Big/ \left\{c_{ij\varepsilon_{ij}}\right\} \le D, \tag{17}$$

$$\sum_{\{i,j\}} c_{ijn_{ij}} \le C, \tag{18}$$

it can be easily solved by consecutive increasing C by ΔC and later on solving the direct problem (12-13). Increasing value C proceeds until relation (17) starts to hold.

6. Numerical example

We will consider a small-scale PERT-COST type project comprising 12 activities with deterministic activity durations. The project's initial data is presented in *Table 1*. The project's budget $C = 111$, cost value step $\Delta C = 1$, relative accuracy $\delta T = 0.01$.

By implementing *Step 3* of the heuristic algorithm (see *Section 5*) the trivial feasible budget reassignment among activities is as follows: $C_{12} = 9$, $C_{13} = 13$, $C_{14} = 14$, $C_{23} = 10$, $C_{25} = 14$, $C_{26} = 7$, $C_{34} = 5$, $C_{35} = 10$, $C_{36} = 15$, $C_{45} = 7$, $C_{46} = 5$, $C_{56} = 2$.

Table 1. The project's initial data

$i,\ j$	C_{ij}	t_{ij}
1, 2	6, 7, 8, 9	10, 8, 6, 5
1, 3	10, 11, 12, 13, 14	28, 26, 24, 20, 18
1, 4	10, 11, 12, 13, 14, 15	18, 17, 16, 14, 12, 10
2, 3	9, 10 ,11	15, 13, 11
2, 5	12, 13, 14, 15	12, 11, 10, 8
2, 6	6, 7, 8	22, 18, 14
3, 4	2, 3, 4, 5, 6	18, 17, 16, 15, 12
3, 5	8, 9, 10 ,11	12, 10, 8, 6
3, 6	14, 15, 16	10, 8, 6
4, 5	5, 6, 7, 8	12, 11, 10, 9
4, 6	4, 5, 6	20, 16, 12
5, 6	1, 2, 3	15, 10, 6

The computational process of the algorithm is represented in *Table 2*:

Table 2. Iterative computational process of budget reassignment

(i,j)	C_{ij}	t_{ij}	CAR_{ij}	C_{ij}	t_{ij}	CAR_{ij}	C_{ij}	t_{ij}	CAR_{ij}	C_{ij}	t_{ij}	CAR_{ij}	C_{ij}	t_{ij}	CAR_{ij}	C_{ij}	t_{ij}	
1, 2	9	5	0.9	9	5	1	9	5	0.89	9	5	0.89	9	5	0.89	9	5	The iterative process terminates
1, 3	13	20	1	14	18	1	14	18	1	14	18	1	14	18	1	14	18	
1, 4	14	12	0.34	14	12	0.36	14	12	0.4	14	12	0.4	10	18	0.6	13	14	
2, 3	10	13	0.9	10	13	1	11	11	0.89	11	11	0.89	11	11	0.89	11	11	
2, 5	14	10	0.33	14	10	0.25	12	12	0.425	12	12	0.5	12	12	0.436	12	12	
2, 6	7	18	0.42	7	18	0.375	7	18	0.46	7	18	0.5	7	18	0.51	7	18	
3, 4	5	15	1	5	15	1	6	12	1	6	12	1	6	12	1	6	12	
3, 5	10	8	0.32	10	8	0.32	10	8	0.36	8	12	0.64	11	6	0.286	8	12	
3, 6	15	8	0.24	14	10	0.28	14	10	0.3125	14	10	0.357	14	10	0.37	14	10	
4, 5	7	10	1	7	10	1	7	10	1	8	9	0.9375	8	9	1	8	9	
4, 6	5	16	0.8	5	16	0.8	5	16	0.8	5	16	1	6	12	0.8	6	12	
5, 6	2	10	1	2	10	1	2	10	1	3	6	0.9375	3	6	1	3	6	
T_{cr}	55			53			50			46			45			45		
Iteration No.	Feasible solution			1			2			3			4			5		
Iterative change ω				0.036			0.056			0.08			0.022			0		

It can be well-recognized that the iterative quasi-optimization process took only 4 iterations in order to reduce the critical path length from $T_{cr}=55$ (trivial feasible solution) to $T_{cr}=45$ (the quasi-optimal solution). Thus, the iterative procedure proves to be efficient. Unfortunately, we have not proved the convergence of the heuristic algorithm.

The quasi-optimal solution is as follows:

$C_{12}=9$, $C_{13}=14$, $C_{14}=10$, $C_{23}=11$, $C_{25}=12$, $C_{26}=7$, $C_{34}=6$, $C_{35}=11$, $C_{36}=14$, $C_{45}=8$, $C_{46}=6$, $C_{56}=3$ (quasi-optimal *Version A*), or

$C_{12} = 9$, $C_{13} = 14$, $C_{14} = 13$, $C_{23} = 11$, $C_{25} = 12$, $C_{26} = 7$, $C_{34} = 6$, $C_{35} = 8$, $C_{36} = 14$, $C_{45} = 8$, $C_{46} = 6$, $C_{56} = 3$ (quasi-optimal *Version B*).

Both versions yield in the same result.

7. Conclusions

1. The newly developed algorithm is easy in usage and effective in practice. Its implementation requires mostly no more than $3 \div 5$ iteration.

2. The algorithm has been widely used both for medium- and large-scale projects with the number of activities exceeding $50 \div 100$. In all cases the algorithm performed well and the number of iterations did not exceed 5.

3. The algorithm can be realized on the basis of classical algorithms which are widely used in network planning and are described in many textbooks on project management.

4. The model suggested in this paper is open for various modifications: e.g., instead CAR values other terms defining the closeness of activities to the critical area and, thus, the level of their influence on the project's duration, may be implemented. However, those modifications are not essential from the principal point of view.

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Dr. Greenberg devotes major part of his time and energy to the community. As such he established with other the Israeli chapter of The Transparency International Organization (TI), and serves as the CFO of the organization. He also serves as a director in several municipal firms, including: the Economic firm of Ariel and the Water & Sewage firm of Ariel.

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