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OPTIMIZING THE PROJECT DEVELOPMENT IN TRANSPORTATION SYSTEMS: ECONOMICAL AND MATHEMATICAL MODELS

ABSTRACT

Construction of high-speed transportation systems often requires calendar planning of the job complex. This paper describes an optimized model of construction project, which includes time parameters as well as cost factors. Project optimization can be achieved by solving the following two problems:

1) *minimizing expenditures within the predetermined duration of construction;*
2) *determining the minimum duration of project construction under the set spending level.*

Both tasks are based on the idea of reducing the duration of certain sequence of operations down to the set level, ensuring the highest effect of accelerating the construction. Under the known time-cost relationship, the optimal solution can be reduced to search for such types of activities within the network model, acceleration of which is the most efficacious in terms of both spending and finishing the overall project. The algorithm for solving the above problems using the network model of job complex is offered in the current paper. This method can be used for planning and managing the work logistics/calendar in construction and related types of industry, for research and development projects in other areas.

KEY WORDS

railway building, duration of project construction, cost of construction, network, optimization

After the World War II, the European railways lost their advantage compared to automobile and air transportation. This was prompted by demands of decreasing the delivery time when transporting passengers or cargo and increasing mobility of direct connections, and backed up by the rapid development of auto and air traffic. The latter became possible due to such factors as an intensive construction of the network of modern automobile roads and airports, spurt in production of large trucks and cargo planes. Relatively low cost of motor fuel contributed to this situation.

Only when the modern high-speed railroads became available, railway transport regained its competitiveness compared to the means of air- and auto-transportation, especially against the background of the ecological problems of the last decade.

Unification of Europe, disintegration of the former USSR, and expansion of the European Union to the East predetermined the idea of creating the transcontinental network of railroads in Europe and Eurasia from Atlantic to the Urals and further up to the Pacific coast. The idea became especially attractive with new developments in the area of magnetic cushion transport. Such projects have been realized in Germany, Japan, and the USA. Russia is also currently conducting research in this area.

The project of creating the transcontinental railway line the Urals-Moscow-Minsk-Warsaw-Berlin-Hannover-Frankfurt-Stuttgart-Luxemburg-Paris has been discussed since 1990-s. Currently, at the distances under 500 km, railway transportation becomes advantageous, especially for passengers. Modern high-speed railway trains (e.g., TGV in France, ICE in Germany) cover this distance faster, more efficiently, and ecologically safer than automobiles.

Optimized coordination of construction of separate network lines with the construction-related spending of finances becomes of primary importance within the framework of the whole transcontinental project. This problem can be successfully solved using the network model of the complex of tasks, or PERT (Program Evaluation and Review Technique) cost.

Two major aspects can be identified in the approach used for optimization:

1) minimizing expenditures within the predetermined duration of construction;
2) determining the minimum duration of project construction under the set spending level.

Both tasks are based on the idea of reducing the duration of certain sequence of operations down to the set level, ensuring the highest effect of accelerating the construction. The solution can be found using the following confining factors:

– acceleration should be applied only to operations influencing the general duration of construction;

- reduction of terms should not exceed the technologically achievable levels;
- the additional expenses per unit reduction of project duration should be minimal.

The latter criterion determines the priority in choosing the network operations requiring reduction of construction terms.

The speed of carrying out certain operations and the levels of expenses on these operations are directly related: as a rule, increased activity requires increased spending of resources, and decreased spending leads to slowing down of the operations.

The complex of operations P presented as a graph, features: if a certain apex $_k \in$ (excluding the initial and the final ones), then there always are apices P_i and P_j from the multitude P, where arcs also belong to the multitude P.

The duration of operations and the moments of beginning and ending of operations determine certain plan (graph) {t, T}, where t and T – vectors with coordinates t_{ij} and T_I, respectively. Each operation q_{ij} corresponds to numbers u_{ij}, D_{ij} (duration of operation), so that

$$0 \le d_{ij} \le t_{ij} \le D_{ij}$$

Let each arc on the graph correspond to a non-negative number $_{ij}$ representing capacity of an arc. If we view such a graph as a railway network, apices of which are the railroad stations, and arcs are the parts of the railroad, then the arc's capacity can be interpreted as the amount of a certain cargo transported from P_i to P_j per unit time.

Consider that arc capacity q_{ij} equals a_{ij} if the job (operation) is critical and $t_{ij} > d_{ij}$;, capacity equals zero if the job is non-critical; capacity of an arc is infinite if the job is critical and $t_{ij} = d_{ij}$. Another important characteristic of the network is flow u_{ij} interpreted as the amount of cargo transported along the arc per unit time. Let us designate the sub-multitude of arcs entering the apices of the graph P_i as U_i^-, and sub-multitude of arcs exiting P_i as U^+. For the whole multitude of graph arcs, determine the function:

$$f(u_i) < a(u_i), \quad i = 1, ,2, 3 \ldots n$$

For all the graph apices, except for the initial P_o and the final P_n:

$$\sum_{u \in u_i^-} t(u) - \sum_{u \in u_i^+} f(u) = 0$$

Consequently, the flow coming from P_o, should be equal to the sum of flows coming into P_n, i.e.

$$\sum_{u \in u_i^- p_0} t(u) - \sum_{u \in u_i^+ p_n} f(u) = \omega$$

where

ω – size of the general flow coming from the initial network apices into the final apices.

If we designate the multitude of events P_j on the critical path as F, then obviously the initial and the final event also belong to F, i.e. $P_o \in$ and $P_n \in$. Let us designate as R the multitude of arcs belonging to the network (P_i, P_j) in which at least one end is not located on the critical path, i.e. it does not belong to the multitude F.

The above-mentioned problem will look as follows:

Find minimum function

$$Z = \sum_{(P_i, P_j) \in P} [-a_{ij}(T_j - T_i) + b_{ij}]$$

under the limitations:

$$a_{ij} \ge 0; \quad b_{ij} \ge 0$$
$$T_j - T_i \ge d_{ij} \qquad \text{for all } (P_i, P_j) \in R$$
$$T_j = T_j^{(0)} = T_j^{(1)} \quad \text{for all } (P_i, P_j) \in F$$

and

$$Z = \sum_{(P_i, P_j) \in P} \frac{a_{ij}}{T_j - T_i}$$

under the limitations:

$$a_{ij} \ge 0$$
$$T_j - T_i \ge d_{ij} \qquad \text{for all } (P_i, P_j) \in R$$
$$T_j = T_j^{(0)} = T_j^{(1)} \quad \text{for all } (P_i, P_j) \in F$$

The initial plan would have the minimum cost among the plans realized during the shortest period of time acceptable for a certain complex of operations.

The duration of operations can be determined from the following expression:

$$t_{ij} = \min\{D_{ij}; T_j - T_i\}$$

and the optimized plan would even allow time reserve.

The so-called reserve problem of cost minimization can be formulated in a general form as follows: Given: each of the operations (P_i, P_j) for a project has the minimum duration of its execution d_{ij} and the time of completing the total complex of operations T_n. It is necessary to determine the times T_j of events P_j (j = 1, 2, 3 ... n) so that, out of all the possible plans that could be realized during the time T_n, the required plan had the minimum cost, i.e. to find the minimum function

$$Z = \sum_{q_{ij} \in P} f(t_{ij})$$

under the limitations:

$$T_j - T_i - t_{ij} \ge 0$$
$$d_{ij} \le t_{ij} \le D_{ij} \qquad \text{for all } q_{ij} \in P$$
$$T_0 = 0, T_n = \lambda$$

This problem described in terms of linear parametric programming can be reduced to the search of optimal plans depending on the parameter λ. Its numeric solution can be obtained using the modified algorithm of Ford-Falkerson for the maximum flow in the network.

The aggregated block-scheme of calculations is presented at the end of this paper.

The key point in solving the problem of optimized planning based on the network model is determining the relationship between time and cost of operations comprising the job complex.

When determining such a correlation, the best results can be obtained by statistical analysis of the actual data. This calculation method allows taking into account influence of a variety of factors on the construction process.

If the actual data are not available, it is possible to use direct calculation based on the analysis of various logistical schemes in construction. Each method should research the area of changing the direct spending function determined by the possibility of saturating the job front with non-accumulating resources. In general, decreased duration of certain operations can be reached in either intensive or extensive way.

Intensive acceleration of operations is achieved by modernizing the logistics, rationalizing the adjuvant manufacturing, improving the use of construction mechanisms, increasing the professional educational levels of labour. Extensive acceleration can be a result of saturating the job front with non-accumulating resources such as human resources, devices, mechanisms, which cause one-time increase in cost of operations due to transporting, installation and dismantling of construction devices and mechanisms, constructing auxiliary devices, etc.

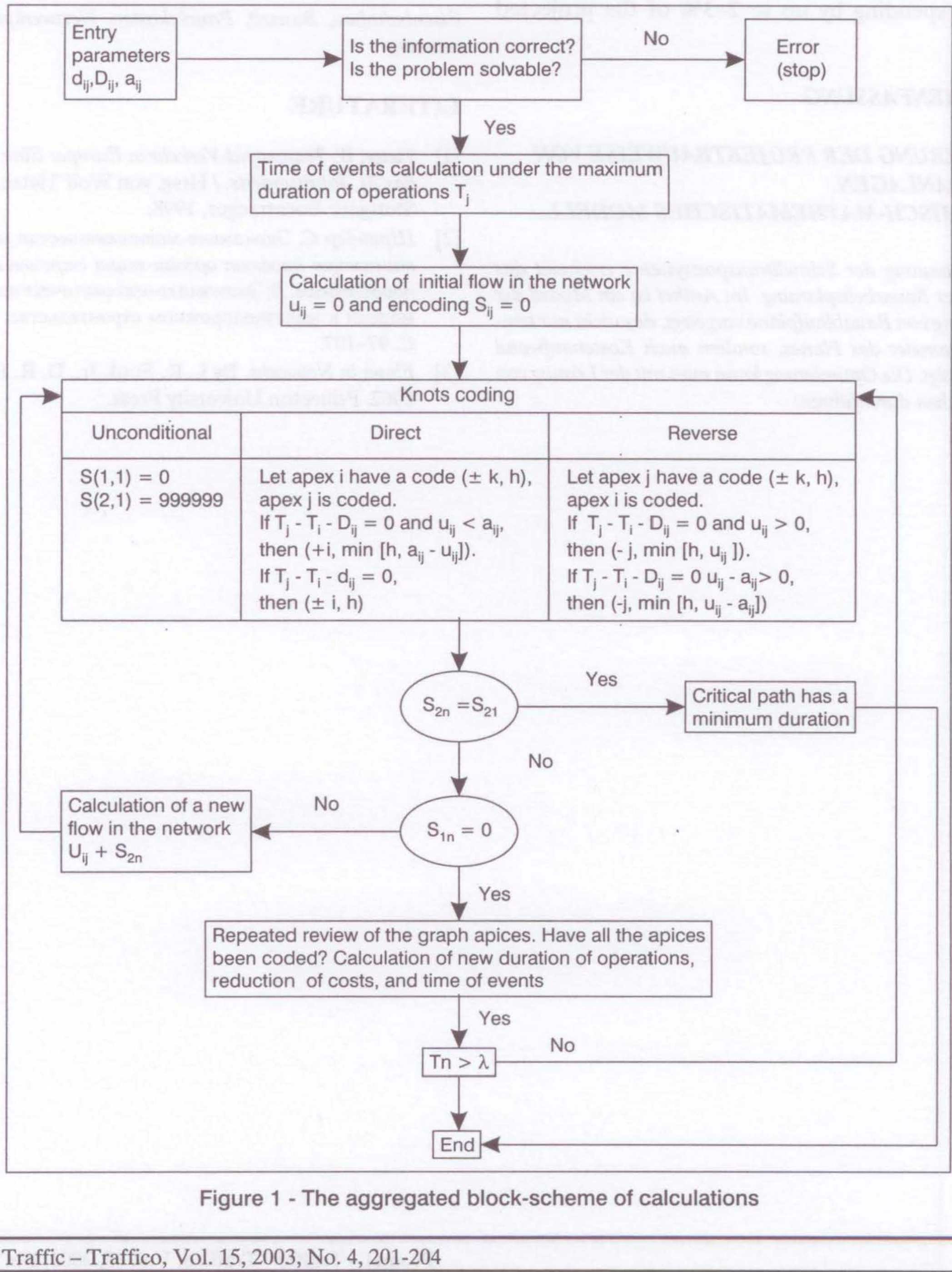

Figure 1 - The aggregated block-scheme of calculations

Calculated correlations between time and spending for certain types of construction operations comprising construction of railroads should take into account its technological peculiarities, possible intensity of resource consumption, transportation costs of building materials and constructions to the sites of their temporary use, changes in spending on the necessary temporary constructions and their shifting along the job front.

Optimized network models of railway lines construction based on the method described above, can decrease the duration of construction operations by 10–12% on the average in comparison with the standard terms, while simultaneously reducing the total spending by up to 2–3% of the projected costs.

ZUSAMMENFASSUNG

OPTIMIERUNG DER PROJEKTBAUWEISE VON FÖRDERANLAGEN. ÖKONOMISCH-MATHEMATISCHES MODELL.

Bei Erbauung der Schnelltransportsysteme erscheint das Problem der Bauarbeitsplanung. Im Artikel ist ein Modell der Optimierung von Bauablaufpläne vorgelegt, das nicht nur temporale Parameter des Planes, sondern auch Kostenaufwand berücksichtigt. Die Optimierung kann man mit der Lösung von zwei Aufgaben durchführen:

- *Minimierung der Projektkosten bei der vorgegebenen Zeitdauer;*
- *Feststellung der allerkürzesten Bauzeit bei den vorgegebenen Gesamtkosten.*

Alle beide Aufgaben gründen sich auf Kürzung der Dauer gewisser Abfolge von Arbeiten. Dabei muss man die Kosten für Arbeitsbeschleunigung minimieren. Die optimale Lösung soll man bei bestimmten Abhängigkeiten „Zeit – Kosten" erreichen. Es ist ein Algorithmus der Lösung genannter Aufgabe, in dem ein Netzwerkplan zugrunde liegt, vorgelegt. Die Methodik kann man wirkungsvoll bei der Planung und Leitung an der Industrie, Baubetrieben und bei der Durchführung von Projekt- und Versuchungsarbeiten verwenden.

SCHLÜSSELWÖRTER

Eisenbahnbau, Bauzeit, Projektkosten, Netzwerkplan, Optimierung

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