Analytical models of decision-making theory in digital transport logistics

A Terentyev¹, M Karelina² and E Karelina³

¹Saint-Petersburg State University of Architecture and Civil Engineering, Saint-Petersburg, Russia
²Moscow Automobile and Road State Technical University (MADI), Moscow, Russia
³Moscow State Technological University “STANKIN”, Moscow, Russia

E-mail: karelinamu@mail.ru

Abstract. The active introduction of information and communication (digital) technologies into the modern reality of transport systems operation requires the development of modeling methods for the creation of software that allows to do the following: determine the formal efficiency of decisions made in digital transport systems (DTS); process large volumes of DTS data; perform analysis of DTS functioning environment using artificial intelligence algorithms, analytical analogues of neural networks, etc. A digital transport system, being a complex system, is determined by a large set of formalized indicators (database) and requires finding effective solutions for a sufficiently large number of criteria or signs of effectiveness. Obtaining reliable solutions in multi-criteria information situations causes difficulties, which are objective. In most cases modern mathematical models artificially reduce multi-criteria information situations to single-criteria categories. This approach, based on the use of integral criteria, has a fundamental disadvantage - the use of integral criteria to obtain estimates of the efficiency of actions or processes in complex systems is characterized by a high level of subjectivism. In this case, the obtained solution may be acceptable, but not an objective result. Therefore, it is necessary to develop mathematical models for solving multi-criteria problems applicable to the solution of problems in complex transport systems, allowing one to operate in the environment of large databases for operational reconfiguration of a management system in conditions of uncertainty and/or possible counteraction of the external environment. The article presents the results of development of mathematical methods of modeling, which allow us to construct algorithms for solving optimization tasks, formulated as multi-criteria models and in the presence of a high degree of uncertainty in the interaction of the system with the environment.

1. Introduction

The achieved level of organizational and technological development in transport systems requires introducing the theory of complex systems management into practice. This is especially important for efficient management, since the level of complexity of interaction between elements in the systems designed and under study is increasing all the time, and this requires developing new methods of data processing and analysis in large volumes. Modern management practices in the DTS require consideration of a huge number of factors, including those of a cognitive nature. Solutions to these problems are often beyond the scope of general system theory, and a compromise must be found.
between system complexity and a simple model. In practical management tasks, it is often necessary to determine the efficiency of a system in multi-criteria conditions to achieve compromise solutions.

2. Problem Statement
As a rule, the solution of any optimization task aimed at determining the most optimal use of the system resources starts with the selection of performance criterion or criteria. This is an important stage, as incorrect selection of performance parameters can lead to completely wrong decisions on resource allocation in the system under study, and the selection should be based on at least two considerations: performance parameters should reflect the main objective of the system task and should be expressed in quantitative terms. However, as a rule, in practice, when solving system problems under conditions of multi-criteria, a fundamental mistake is made by implementing a compromise approach: multi-criteria information situations are artificially reduced to single-criteria ones. At the same time, the concept of efficiency, which is a complex category, is reduced to a single characteristic, replacing the complex objective causal relations in the system. This approach, based on a single integral criterion, has a fundamental disadvantage. The use of integral criteria for comparative evaluation of complex organizational and technological processes is characterized by a high level of subjectivism. Taking the above into account, let us define that when a multi-criterion task is reduced to a single criterion and optimization of management processes in a complex system is carried out according to a single criterion, the solutions may prove to be acceptable, but are not an objective result.

When making a decision on the expediency of applying a particular method of efficiency assessment or method of determining the effectiveness of actions in a DTS, it is necessary to determine which class of complexity the system under study belongs to and which scientific direction is more appropriate for this class of systems. The Hiroki Sayama study [1] is considered to be an important work in the development of the theory of complex systems (TCS); according to this work, the TCS brings together a number of scientific directions, including the general theory of systems (GTS) and is more general according to the classical approaches of systems analysis. The structure of the TCS is shown in Figure 1 [1].

![Figure 1. TCS structure.](image-url)
susceptible, valid and reliable one, and notes that these important characteristics are absent in the classic GTS.

3. Research questions
Being a complex system, the DTS belongs to the class of dynamic systems. The dynamic systems theory (DST) today occupies a special place in the TCS, based on its definition. The DST is a system the state of which is determined by a set of predetermined laws of purposeful change of system parameters [5]. Figure 2 shows the structure of complex systems, signs of which an intelligent transport system possesses (ITS) [9].

Figure 2. An approximate structure of complex systems integrated into ITS [10].

As can be seen from Figure 2, the DTS has all the mandatory features typical of any complex system, such as a large number of connections and elements, and refers to complex systems according to all criteria of the GTS and TCS [6,7,8]. Like any complex system, the DTS requires the ability to process "big data" [10], determined by the presence of a large information volume of processed data. Therefore, when forming the model and optimization methods in the DTS it is necessary to do the following:

1. Formalize the complexity of the DTS based on the information states of the system, which, in turn, are determined by possible internal and external disturbances;
2. Choose the DTS dividability criteria, taking into account the heterogeneity of the system elements [11];
3. Develop tools for management and optimization of the DTS operation taking into account the potential capabilities of the existing methods of decision-making theory.

Let us consider the possibility of processing "big data" as a tool based on mathematical models of decision-making theory. An example of this approach may be the method of measuring formal efficiency or analysis of a functioning environment - Data Envelopment Analysis (DEA), which is based on the construction of the efficiency boundary and is widely used today [12, 13, 14]. This method was proposed in 1978 by American scientists A. Charnes, W.W. Cooper, E. Rhodes [15], who, in turn, had relied on the ideas by M.J. Farrell [17]. This method is used to determine efficiency in social and organizational systems for homogeneous facilities.

4. Research results
The essence of the method is to determine the difference between the ratio of the results and production capabilities of the object under study. As a rule, the boundaries of production capabilities are unknown and their determination is performed either by using the DEA method or on the basis of empirical data included in the study sample [17]. The boundaries of production capabilities show an alternative (maximum possible) solution with the available resources of the system under study. The
DEA method is being actively improved and developed today. Currently there is no exact correspondence between the term Data Envelopment Analysis and the common Russian equivalent even in the terminology of the method. In [18] the following option is proposed - "analysis of the functioning environment", but in our understanding a more appropriate term is "analysis of the research environment", as the DEA method can be used in various fields of activity and is aimed at improving the efficiency of their functioning systems, and thus at exploring the possibilities of complex systems. This method has a number of undeniable advantages:

1) the method allows processing quite a number of "inputs" and "outputs" at the same time, each of which can be defined in different units of measurement;
2) the method may take into account the impact of the environment on the complex system under study, i.e. variable factors, in particular the environment;
3) the method does not require a priori determination of coefficients of relative importance or weighting coefficients for variables that are "input" and "output" parameters in optimization tasks;
4) the method allows one not to impose restrictions on the functional form of dependencies between "outputs" and "inputs";
5) the method makes it possible to take into account, if necessary, preferences or priorities concerning the significance of certain input or output parameters;
6) the method lets one make a specific assessment of the required changes in the inputs and outputs, which will bring ineffective research objects closer to a certain efficiency boundary;
7) the method allows us to form a Pareto-optimal set, which corresponds to the effective state of the object;
8) the method focuses on identifying "best practice" through objective analytical methods of decision making theory rather than subjective predictive "trends" obtained through the use of regression or correlation analysis methods.

An important property of the DEA method is the ability to define a Pareto set or a set of effective plans [19, 20].

The disadvantage of the method is the DEA procedure for determining the boundaries of production capabilities of a system object based on empirical data. It is possible to solve this problem more effectively by applying analytical methods of determining the values included in the Pareto set, as well as applying methods of linear programming.

Let us formulate the main provisions of the proposed algorithm of the proposed approach for determining the boundaries of the possibility of influencing the object under study. The matrix of efficiency of actions on the whole distribution of information states of the research environment is as follows:

\[
\|a_{ij}\| = \begin{pmatrix}
a_{11} & a_{12} & \ldots & a_{1n} \\
a_{21} & a_{22} & \ldots & a_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
am_{m1} & a_{m2} & \ldots & a_{mn}
\end{pmatrix}
\]  

(1)

where \(m\) is the number of possible actions; \(n\) – the number of possible information states of the research environment and their corresponding performance criteria; \(a_{ij}\) – efficiency of the \(i\)-th action for the \(j\)-th state, \(i = 1, m, j = 1, n\).

In studies [21, 22, 23] it has been established that when solving the tasks related to the definition of Pareto set and provided the function of efficiency index is continuous from the change of the research medium state vector, it is possible to apply the methods of linear programming. Then the distribution of coefficients of relative importance (CRIs) is subject to the following restrictions

\[
0 \leq c_j \leq 1, \quad j = 1, n, \quad \sum_{j=1}^{n} c_j = 1,
\]

(2)

i.e. determined by a set of \((n - 1)\) independent variables.

Let us put into the sequence the coefficients’ values \(c_j\):
If $n \geq 3$, then the distribution field of coefficients of relative importance in the Cartesian coordinate system evolves into a rectangular triangle with single catheters (Figure 3). In this case, the number of subsets of CRI ratios is $P_3 = 3! = 6$.

If $n = 4$ (Figure 4), the number of subsets of CRI ratios is $P_4 = 4! = 24$.

The developed approach allows formulating an algorithm for determining the boundaries of the system under study as follows: for each variant $i$ the problem of linear programming is solved:

$$
\begin{align*}
D_i = \sum_{j=1}^{n} a_{ij} c_j & \to \max, \\
\sum_{j=1}^{n} c_j &= 1, \quad 0 \leq c_j \leq 1, \quad c_j \geq c_{j+1}, \quad j = 1, n-1.
\end{align*}
$$

(4)

The CRI values are then determined analytically:

$$
\begin{align*}
c_j &= \begin{cases} 
\frac{1}{k}, & \text{if } j = k \\
\frac{j}{k}, & \text{if } j < k, \text{ where } \lambda = \frac{n-1}{n} \\
1 - \frac{\lambda}{n-k}, & \text{if } j > k
\end{cases}
\end{align*}
$$

(5)
Where index $k$ is defined from the condition $a_{kj} = \max_j a_{ij}$.

5. Conclusions
Active introduction of information-switching or digital technologies into the modern reality of transport systems functioning allows processing quite a lot of "inputs" and "outputs" to the DTS simultaneously, providing the necessary volume or "database" of optimization parameters. Integration of Data Envelopment Analysis methods and the proposed solution into a single analytical platform will allow us to:

- determine formal efficiency in a DTS;
- process large volumes of DTS data;
- perform the analysis of the DTS functioning environment using artificial intelligence algorithms with an unlimited number of criteria or signs of efficiency.

The solution of this problem will allow us not only to obtain the required Pareto-optimal solutions, but also significantly reduce the number of computational procedures required for their search.

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