Effective strategies for multimodal transportation network

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Abstract. In accordance with the enlarged functional structure of the multimodal transportation network designing methodology, the article describes the methods of the forming of the Area of effective strategies of the multimodal transportation network development. In this study, a multimodal transportation network is considered as a set of multimodal transportation corridors consisting of multimodal transportation hubs and transportation links of various modes of transport. The methods of system analysis, mathematical logic, mathematical modeling of processes and systems were used in the development of the methodology. To reduce the dimension of the problem used: decomposition of the multimodal transportation network shape; the principle of setting the initial conditions; technological relations that determine the sequence of activities in time, their conditionality in relation to each other and compatibility. The proposed method allows to form the area of effective strategies for changing the shape and capacity of multimodal transportation network for set of estimated cases. Estimated cases specify variants of required traffic volumes and estimated schemes of multimodal transportation network shape for different scenarios of socio-economic development of the country and its regions, taking into account the impact of external and internal factors on decision-making, generating uncertainty of initial information. The formed area of effective strategies is used to make the optimal design decision to change the shape and capacity of multimodal transportation network.

1. Introduction

The development of transport infrastructure should precede the socio-economic development of the country and its regions. The high cost of transport devices and structures requires to create a science-based approach to decision-making in the complex transport system designing as multimodal transportation network (MTN). It’s proposed to consider the MTN as a set of multimodal transportation corridors (MTC), consisting of multimodal transportation hubs (nodes) and transportation links of the various modes of transport [1].

The various models, methods and techniques for the solution of separate problems of functioning and development of multimodal transportation corridors are offered in the many existing transport researches of domestic and foreign scientists and experts [2-19 and other].

The analysis of these scientific papers, given in [20-22], showed the relevance of the problem of transport infrastructure development for multimodal transport and confirmed the need to develop a methodology for designing the complex development of MTN, as a science-based tool for solving strategic problems of transport development in Russia [1].

In [20, 21] the fundamentals of this methodology are defined.
According to the logic of the design process the enlarged functional structure of the methodology is represented by six following stages [20]:

1. Statement of the problem of multimodal transportation network designing.
2. The development of the MTN’s shape variants.
3. Forming of set of possible strategies of development for objects of multimodal transportation network.
4. Forming of the area of effective strategies of multimodal transportation network development.
5. Decision maker’s work with the effective strategies area for decision making.
6. Support for the execution of the adopted strategy.

This article describes the methods of forming of the effective strategies area of multimodal transportation network development to select the optimal design solution.

2. Materials and Methods

On the basis of scientific papers [1, 23, 24], using the theory of systems, the developed set-theoretical models of MTN and its development strategies [20, 21] are the mathematical basis of the multimodal transportation network designing methodology. Using a four-level decomposition of MTN, these set-theoretical models allow to aggregate the results of the local solutions (for MTN’s objects development) into a single MTN’s development strategy.

In [20] proposed the methods of forming of initial set of possible development strategies for MTN’s objects \(\mathcal{S} = \{\Omega_{\text{IMC}_{i r}}\}\). Each such strategy is considered as a result of the local solution. On the basis of [20, 21] in accordance with the [22], these results are aggregated in the strategies of multimodal transportation network development \(\mathcal{S}^{MTN}(t) = \{\Omega_{\text{IMC}_{i r}}^{MTN}\}\).

3. Results

The area of effective strategies of multimodal transportation network development \(\mathcal{S}^{MTN}(t)^*\) is used in the multimodal transportation network designing methodology to select the optimal MTN’s development strategies from the set of competitive strategies under different scenarios of socio-economic development of the study region, taking into account the impact of various factors on decision-making.

The forming of area of effective strategies of multimodal transportation network development \(\mathcal{S}^{MTN}(t)^*\) requires the preparation of the following initial data:

- the set of estimated cases \(\mathcal{R}_{\text{S}tr_{i r}}\). In accordance with the set-theoretical model (2) [22] each estimated case includes: a scenario of socio-economic development of the region under study \(\mathcal{S}^{\text{S}tr_{i r}}\), required traffic volumes on MTC \(\mathcal{V}_{\text{G}_{i r}}\) and the corresponding schemes design of MTN shape \(\mathcal{R}_{\text{str}_{i r}}\). Estimated cases allow to take into account different scenarios depending on the impact of political, economic, social and other factors affecting the MTN from the outside. Estimated cases allow to look for solutions in conditions of uncertainty;

- the initial set of possible development strategies for MTN’s objects \(\mathcal{S}^{\text{O}M}_{\text{IMC}_{i r}}\). This set is formed by the methods in [20].

On the basis of the four-level decomposition of MTN, the area of effective strategies of multimodal transportation network development \(\mathcal{S}^{MTN}(t)^*\) forms in three stages.

At the first stage, the initial set of development strategies of multimodal transportation network \(\mathcal{S}^{MTN}(t)\) is formed for each estimated case \(\mathcal{R}_{\text{S}tr_{i r}}\). The strategies are aggregated sequentially by levels of the four-level decomposition of MTN; from lower object’s lever to upper MTN’s level. In the process of this aggregation, it is necessary to take into account the technological relations that determine the sequence of activity’s implementation in time, their conditionality in relation to each other and compatibility on MTN objects \(\mathcal{H}_{\text{M}}\). The measure (activity) aimed at changing the shape and capacity of the MTN object (development of MTN object) is a set of actions to change the technical condition of...
the object to achieve the objectives of the operation and development of a multimodal transport network in this study [21].

For this purpose, it is necessary to execute the following steps by levels of the hierarchy.

IV level of the hierarchy.

a) to form possible strategies for the development of transportation links from the strategies for the development of intermediate points and sections, using the method of direct search:

$$
\text{Str}^{ZV_{iMTY} - jMTY}_{\text{irz}}(t) = \times_{p \in \text{Pn}_{izv}} \times_{u \in \text{Uch}_{izv}} \text{Str}^{u}_{\text{irz}}(t),
$$

$$
i_{TR} \in \{GT \lor AT \lor MT \lor RT \lor TT \lor VT\}, p \in \text{Pn}_{izv}, u \in \text{Uch}_{izv},
$$

(1)

to form possible strategies for the development of multimodal transportation hubs (MTH) from the strategies for the development of MTH objects by each mode of transport:

$$
\text{Str}^{TR}_{\text{irz}}(t) = \text{Str}^{GR}_{\text{irz}}(t) \times \text{Str}^{ST}_{\text{irz}}(t) \times \text{Str}^{SP}_{\text{irz}}(t) \times
$$

$$
\times \text{Str}^{PAS}_{\text{irz}}(t) \times \text{Str}^{ED}_{\text{irz}}(t) \times \text{Str}^{PS}_{\text{irz}}(t),
$$

$$i_{TR} \in \{GT \lor AT \lor MT \lor RT \lor TT \lor VT\};
$$

(2)

b) to determine the investment volumes for the implementation of activities for each strategy for changing the shape and capacity of the transportation links and MTH within a single mode of transport:

$$
K\left(t, \text{Str}^{ZV}_{\text{irz}}\right) \nabla K\left(t, \text{Str}^{TR}_{\text{irz}}\right);
$$

c) to exclude from the sets $\text{Str}^{ZV}_{\text{irz}}$ and $\text{Str}^{TR}_{\text{irz}}$ strategies that do not satisfy the condition:

$$
K\left(t, \text{Str}^{ZV}_{\text{irz}}\right) \leq K_{n(i_{irz})}(t).
$$

(3)

III level of the hierarchy.

d) on the basis of the results obtained at IV level of the hierarchy, to form possible strategies for the development of multimodal transportation links (set-theoretical model (9) [25]) and hubs (set-theoretical model (8) [25]), using the method of direct search:

$$
\text{Str}^{ZV}_{\text{irz}}(t) = \times_{TR} \text{Str}^{ZV}_{\text{irz}}(t),
$$

$$
\text{Str}^{MTY}_{\text{irz}}(t) = \times_{TR} \text{Str}^{MTY}_{\text{irz}}(t),
$$

(4)

e) to determine the investment volumes $K\left(t, \text{Str}^{ZV}_{\text{irz}}\right); K\left(t, \text{Str}^{MTY}_{\text{irz}}\right)$ required to implement of activities of the relevant strategies;

f) to exclude from the sets $\text{Str}^{ZV}_{\text{irz}}$ and $\text{Str}^{MTY}_{\text{irz}}$ strategies that do not satisfy the conditions:
II level of the hierarchy.
g) on the basis of the results obtained at III level of the hierarchy, to form possible strategies to change the shape and capacity of multimodal transportation corridors (set-theoretical model (2) [25]), using the method of direct search:

\[ S_{str}^{MTK_{str}}(t) = \times_{MTY_{i}} S_{str}^{Y} (t) \times_{ZV_{i}} S_{str}^{ZV} (t) \]

(6)

h) to determine the investment volumes \( K \left( t, \text{str}_{str}^{MTK_{str}}(t) \right) \) required to implement of activities of the relevant strategies;

i) to exclude from the set \( \text{str}_{str}^{MTK_{str}}(t) \) strategies that do not satisfy the condition:

\[ K \left( t, \text{str}_{str}^{MTK_{str}}(t) \right) \leq K_{n(t)}(t) \]

(7)

I level of the hierarchy.
j) on the basis of the results obtained at II level of the hierarchy, to form initial set of possible strategies for the MTN development (set-theoretical model (1) [25]), using the method of direct search:

\[ c = \times_{\text{str}_{str}^{MTK_{str}}(t)} \]

(8)

At the second stage, the admissible set of strategies of multimodal transportation network development \( \Omega_{DMC_{str}}^{MTN} \) is formed from \( \Omega_{DMC_{str}}^{MTN} \) for each estimated case \( (RS_{str}) \).

For this purpose, it is necessary to execute the following actions:
k) to determine the investment volumes \( K \left( t, \text{str}_{str}^{MTN}(t) \right) \) required to implement of activities of the relevant strategies;
l) to exclude from the set \( \text{str}_{str}^{MTN}(t) \) strategies that do not satisfy the condition:

\[ K \left( t, \text{str}_{str}^{MTN}(t) \right) \leq K_{n(t)}(t) \]

(9)

At the third stage, it’s performed the forming of common area of effective strategies of multimodal transportation network development \( \left( \text{str}_{str}^{MTN}(t)^{+} \right) \) or the area of effective strategies for each estimated case \( \left( \text{str}_{str}^{MTN}(t)^{+} \right) \) separately.

To form the set \( \text{str}_{str}^{MTN}(t)^{+} \) it is necessary to execute the following actions:
m) to determine operating costs for each strategy of MTN’s objects development included in the \( \Omega_{DMC_{str}}^{MTN} \); 
n) to determine reduced construction and operating costs for each strategy of MTN’s objects development included in the \( \Omega_{DMC_{str}}^{MTN} \) (math models (3.55) and (3.56) [20]);
o) to determine reduced construction and operating costs for each strategy of MTN development included in the \( \Omega_{DMC_{str}}^{MTN} \) (math models (3.51) - (3.54) [20]); 
p) to determine the economic efficiency for each strategy of MTN development included in the \( \Omega_{DMC_{str}}^{MTN} \):

\[ \mathcal{E}_{N} \left( t, \text{str}_{str}^{MTN}(t) \right) = HD \left( t, C_{n(t)}^{mtn}(t), f: \text{str}_{str}^{mtn}(t) \rightarrow Em_{mtn}(t) \right) \]

(10)

q) to exclude from the set \( \Omega_{DMC_{str}}^{MTN} \) strategies that do not satisfy the condition:
Forming of the set \( S_{\text{Str}^\text{MTN}(t)^*} \) is performed according to the formula:

\[
\mathcal{E}_{\text{Str}^\text{MTN}(t)^*} = \bigcup_{i \in \text{RS}} \mathcal{E}_{\text{Str}^\text{MTN}(t)^*}, \quad \text{RS} = \{i \in \text{RS} | i = 1, n_{RS}\}. 
\]

4. Conclusions

The proposed methods of forming the Area of effective strategies of the MTN development is used in the multimodal transportation network designing methodology for the subsequent selection of the optimal (best) strategy by the decision-maker. The strategies included in the Area of effective strategies are effective in various scenarios of socio-economic development of the studied region and variants of the required volumes of traffic on multimodal transport corridors. This enables the decision-maker to take into account the influence of factors that create uncertainty of the initial information.

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