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DEMAND FORECASTING AND ADAPTIVE MANAGEMENT OF INTERMODAL TRANSPORT HUBS BASED ON RISK MANAGEMENT AND CROWDSOURCING

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Due to martial law in Ukraine, a significant portion of the transport infrastructure has undergone considerable disruption: dynamic population migration, unpredictable delays, risks of functional failures due to shelling, air raid alerts, or damaged infrastructure. Railway hubs that integrate several modes of transport (metro, buses, trams, etc.) play a crucial role in maintaining population mobility, particularly in crisis situations [1]. Given the limited access to traditional data sources, the use of crowd-sourced data has become especially important for real-time demand forecasting and risk monitoring [2, 3].

The process of managing a transport hub in this study is formalised as an optimisation mathematical model, which incorporates multifactorial data and enables adaptive decision-making in real time. The research focusses on an intermodal transport hub (a railway station and adjacent modes of transport).

The forecast demand on line l at time t , using crowd-sourced and open data, is expressed as follows: $P_t^{in}(l)$, $P_t^{out}(l)$ – number of passengers arriving at or leaving the intermodal transport hub via line l at time t , respectively. These values are modelled as a function of the following parameters: $X_t(l)$: crowdsourced data (mobile GPS tracks, social media, search engine queries); $H_t(l)$ – historical transport demand data (previously recorded demand); S_t – seasonality factors (day of the week, holidays, etc.); E_t – external factors (air raid alerts, shelling, movement restrictions, etc.). Formally:

$$P_t^{in/out}(l) = f(X_t(l), H_t(l), S_t, E_t).$$

This function can be implemented using regression models (e.g. LSTM, Prophet, ARIMA), machine learning models (Random Forest, CatBoost), or neural networks with multifactor input.

The optimisation model includes the following definitions: $T = \{1, 2, \dots, H\}$ – set of discrete time intervals (hours, days); N – number of transport modes at the hub (railway, metro, tram, bus, etc.); $L = \{l_1, l_2, \dots, l_m\}$ – set of routes/lines at the hub; C_l – capacity of line l (in passengers per time interval); τ_{ij} – transfer

time between modes i and j at the hub; $R_t(l) \in [0,1]$ – risk function of line l at time t , taking into account threats (air raids, damage, etc.); $\alpha_t \in \{0,1\}$ – binary variable indicating whether line l is operational at time t (1 – operating, 0 – not operating).

The objective function minimises total costs associated with delays, unmet demand, and risk factors:

$$\min \sum_{t \in T} \sum_{l \in L} [\beta_1 \cdot U_t(l) + \beta_2 \cdot D_t(l) + \beta_3 \cdot R_t(l) \cdot (1 - \alpha_t(l))]$$

where $U_t(l) = \max(0, P_t^{in}(l) + P_t^{out}(l) - C_l \cdot \alpha_t(l))$ – unmet demand due to capacity limits or risks (passengers unable to use the line); $D_t(l)$ – expected delays on line l (estimated via historical or crowdsourced data); $R_t(l) \cdot (1 - \alpha_t(l))$ – penalty for lack of service due to high risk; $\beta_1, \beta_2, \beta_3$ – weight coefficients.

The proposed approach takes into account capacity constraints, permissible transfer time, and risk-related operational constraints on lines.

Line capacity constraint:

$$P_t^{in}(l) + P_t^{out}(l) \leq C_l \cdot \alpha_t(l) + U_t(l), \quad \forall t \in T, \quad \forall l \in L.$$

Permissible transfer time:

$$\tau_{ij} \leq \tau_{\max}, \forall i, j \in N, i \neq j.$$

Operation with risk consideration:

$$\alpha_t(l) \leq 1 - \delta_t(l), \delta_t(l) \in \{0,1\}, \delta_t(l) = 1 \Rightarrow R_t(l) > r_{critical},$$

where $r_{critical}$ – the threshold risk level that prohibits operation of line l .

Thus, the mathematical optimisation model proposed in this research enables intelligent management of multimodal transport hubs under conditions of wartime threats and instability. It allows the transport system to be adapted to current circumstances, including mass evacuation, congestion, route blockages, or infrastructure damage. The integration of crowd-sourced data ensures high flexibility and adaptability. The further development of the model envisages its testing on real-world data and the creation of a digital platform for the real-time management of urban transport in Ukrainian cities.

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