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DEVELOPMENT OF METHOD FOR ANTI-ICING MATERIALS CONSUMPTION OPTIMIZATION DURING WINTER ROAD MAINTENANCE

The object of research is the processes of managing the consumption of anti-icing materials during the winter maintenance of highways. The main hypothesis of the research is the application of mathematical modelling methods to optimize the consumption of anti-icing materials. The study considered the factors that affect the use of both individual types and anti-icing materials as a whole. It was determined that the temperature of the road surface and the selected winter maintenance strategy taking into account the level of service (LOS) are significant factors. A mathematical model of material consumption optimization based on the binary numbering system is proposed. Additional limitations to the model have been established: compliance with the criteria of reliability, preservation of assets, road safety, compliance with user expectations (social factor), environmental friendliness, efficiency of the use of materials. An algorithm for the application of the method of optimizing the consumption of anti-icing materials during the winter maintenance of highways has been developed. It was determined that the developed method solves the main problem of minimizing the costs of anti-icing materials, taking into account the requirements of the level of service, the chosen strategy, the temperature of the road surface and the criteria of impact on winter maintenance. It is proposed to implement the calculation according to this method using the built-in «Parameter selection» function in the Microsoft Excel license environment (USA). The results obtained by the optimization method, based on real data, showed the possibility of saving materials by about 23 %, which confirms the effectiveness of the proposed solutions.

The results of calculations based on the method of optimization of material consumption have practical value and can be used to make management decisions regarding the justification of winter road maintenance operations. The proposed method can be used both for the cost planning phase and in the case of analysis in the post-implementation period. This is an important aspect in the conditions of financial and resource uncertainty, including those related to circumstances of force majeure, in particular, martial law in Ukraine.

Keywords: *optimization method, winter maintenance, anti-icing materials, rate of consumption of materials.*

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1. Introduction

Highway maintenance is the longest phase of the life cycle. An important feature of maintenance is its seasonality and the need to take into account the climate of the service area of the road network. In particular, for the northern and western regions of Ukraine, optimization of winter road maintenance operations is important for ensuring road traffic safety, mobility and productivity of transport systems [1]. According to the Ukrainian Hydrometeorological Center of the State Emergency Service of Ukraine, more than 70 percent of the country's roads are located in regions with periodic snowfall in the winter period with a snow cover of at least 30–40 mm.

The fight against snowfall and its consequences for road organizations is a complex process that requires the coordination of the work of specialized teams, the use of modern technologies, equipment and materials. One of the important tasks of the road service is to optimize the costs of anti-icing materials. A number of researchers of this issue are inclined to the need to take into account the so-called precipitation index, as well as various scenarios of material spreading [2–5] when planning stocks of anti-icing materials. In particular, in studies [3, 4] it is about preventive measures (preliminary treatment of roads), watering with a solution or spreading of dry reagents (or salt). The researchers of works [6, 7] suggest using the life cycle assessment (LCA) method and the road and weather information management system for making management decisions regarding winter maintenance measures (spreading of anti-icing materials or snow clearing of roads). Separate studies [8] emphasized the need to regulate the costs of anti-icing materials from the side of their negative impact on the environment, existing infrastructure facilities, and road users. However, it should be noted that scientists have not sufficiently substantiated the application of one or another mathematical method of calculating the costs of anti-icing materials in various scenarios of material spreading. Thus, the development of a method of optimizing the consumption of anti-icing materials during the winter maintenance of the road network is an urgent scientific task of an applied nature.

The aim of research is to develop a method for optimizing the consumption of anti-icing materials during winter road maintenance. This will make it possible to minimize the social, economic and environmental consequences of the use of chemical reagents, salt and abrasives due to the reasoned choice of the most optimal winter road maintenance strategy.

2. Materials and Methods

Indicators of the effectiveness of anti-icing materials are indicators of how well winter road maintenance operations meet the expectations of the road organization and road users [9]. Thus, *the object of the study* is the processes of managing the consumption of anti-icing materials during the winter maintenance of highways.

Performance of winter operational maintenance of the road network begins with the selection of the most optimal maintenance strategy. One of the most common strategies is the anti-icing strategy. The essence of this strategy is to minimize the time that snow and ice remain on the road surface. In this case, anti-icing materials are used preventively (before the beginning of snowfall) to prevent the formation of a solid compacted layer of snow, and also repeatedly during snow removal. Another strategy is to carry out activities during or after precipitation, taking into account compliance with road safety standards. The main operations in this case are snow removal, compaction and sprinkling with sand or mixtures. According to world experience, the choice of an operational maintenance strategy is regulated by the level of service (LOS) [10, 11]. Making strategic decisions inevitably leads to the need to justify a number of tactical decisions, for example, the time of applying reagents, the norm, the time of mechanical snow removal, etc. (Fig. 1). Each tactical solution is measurable and meets individual LOS requirements regarding reliability, asset preservation, road safety, meeting the needs of road users, compliance with the criteria of efficiency and environmental friendliness of the anti-icing materials used.

Thus, the level of road maintenance in the winter period can be set by the function:

$$LOS_w = f(S, T_V, O, \bar{M}, I_W), \quad (1)$$

where S – winter maintenance strategy; T_V – duration of operations; O – type of operation (tactical decision based on strategy); M – average hourly rate of material consumption; I_W – weather index.

Service level assignment also depends on the following parameters:

– traffic intensity on the site, meaning and category of roads;
– observed rainfall intensity;
– days of the week (working days, non-working days);
– time of day (peak hours).

The calculation of the rate of consumption of materials is based on the assumption that all parameters of the rate are evenly distributed over time.

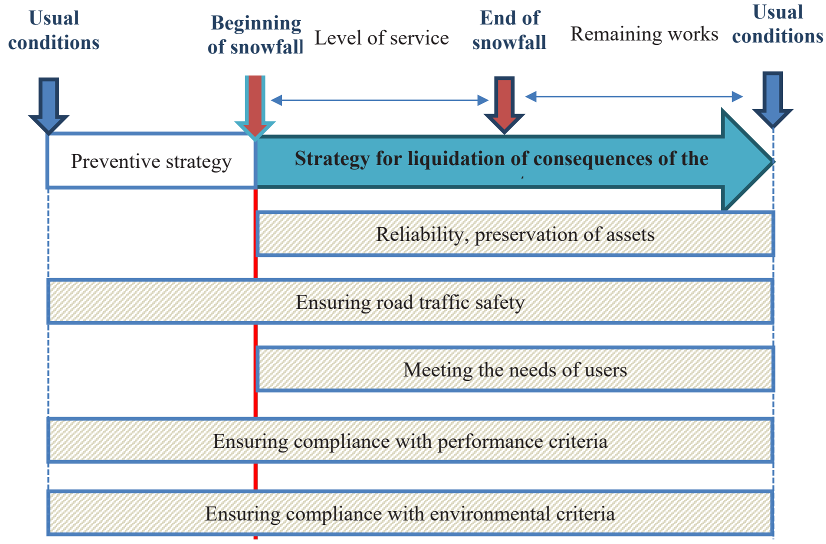

Fig. 1. Tactical and strategic goals of road maintenance in the winter period

The average hourly rate of material consumption for each patrol area is determined by the formula:

$$\bar{M} = \frac{\sum_{i=1}^{i=W}\sum_{j=1}^{j=V}\sum_{t=1}^{t=T} M_{i,j,t}}{X \cdot W \cdot V \cdot T}, \quad (2)$$

where $M_{i,j,t}$ – consumption rate of the i-th anti-icing material at the j-th event at the patrol area for t hours of time, units of measurement according to the type of material; X – number of traffic lanes; W – amount of anti-icing materials; V – number of events (operations) in the patrol area; T – the total duration of the operation.

In the case of the optimization model, formula (2) will have the form:

$$\bar{M} = \frac{\sum_{i=1}^{i=W}\sum_{j=1}^{j=V}\sum_{t=1}^{t=T} M_{i,j,t}}{X \cdot W \cdot V \cdot T} \to \min. \quad (3)$$

With model restrictions:

$$\begin{cases} T \to \min, \\ \bar{M} \ge M_a, \\ V \ge V_a, \end{cases} \quad (4)$$

where M_a – the maximum consumption rate of anti-icing materials; V_a – threshold number of events according to the level of service (LOS).

Consumption of materials, reduced to the length of patrol areas:

$$\bar{Q} = \frac{\sum_{i=1}^{i=W}\sum_{j=1}^{j=V}\sum_{t=1}^{t=T} \frac{M_{i,j,t}}{L_{i,j,t}}}{X \cdot W \cdot V \cdot T}, \quad (5)$$

where $L_{i,j,t}$ – the length of the patrol area where the i-th anti-icing material was used at the j-th event in t hours of time, km.

The material consumption rate can also be calculated per unit area, then in formula (5) instead of the length of the patrol areas, the area variable will be applied:

$$\bar{Q}=\frac{\sum_{i=1}^{i=W}\sum_{j=1}^{j=V}\sum_{t=1}^{t=T}\frac{M_{i,j,t}}{Sq_{i,j,t}}}{X\cdot W\cdot V\cdot T}, \quad (6)$$

where $Sq_{i,j,t}$ – the area of the patrol area where the i-th anti-icing material was used at the j-th event in t hours of time, m^2.

It should be noted that the choice of one or another anti-icing material primarily depends on the temperature of the coating and the selected operational maintenance strategy.

Thus, clarifying the conditions and restrictions, there is a mathematical model of material consumption optimization, which is based on the binary numbering system:

$$\bar{Q}=\frac{\sum_{i=1}^{i=W}\sum_{j=1}^{j=V}\sum_{t=1}^{t=T}\frac{M_{i,j,t}}{L_{i,j,t}}}{X\cdot W\cdot V\cdot T}\rightarrow$$

$$\rightarrow\min\left|\begin{array}{l}1;\forall t^0,\\ M_{i,j,t}\rightarrow\forall M_{i,j,t},S;\\ 0;\forall t^0,\\ M_{i+1,j,t}\rightarrow\forall M_{i+1,j,t},S,\end{array}\right. \quad (7)$$

where t^0 – the temperature of the road surface, °C; 1 – the i-th anti-icing material, corresponds to the temperature conditions of use and the adopted strategy; 0 – the i+1-th anti-icing material corresponds to the temperature conditions of use and the adopted strategy.

Additional restrictions to the adopted strategy are compliance with the criteria of reliability, preservation of assets, road safety, compliance with user expectations (social factor), environmental friendliness, efficiency of the use of materials:

$$\bar{Q}\in f\cup\{F_N,F_A,F_{RS},F_S,F_E,F_{LOS},F_{KPI}\}, \quad (8)$$

where F_N – reliability criterion; F_A – asset preservation criterion; F_{RS} – road safety criterion; F_S – criterion of compliance with user expectations (social factor); F_E – ecological criterion; F_{LOS} – criterion for meeting the requirements of service level standards; F_{KPI} – criterion for the effectiveness of anti-icing materials.

Thus, the sequence of application of the proposed method can be graphically displayed in the form of an algorithm (Fig. 2).

The tasks of the developed method are to minimize the cost of anti-icing materials taking into account the requirements of the level of service, the chosen strategy, the temperature of the road surface and the criteria of impact on winter maintenance. The calculation according to this method can be carried out using the built-in function «Select parameters» in the Microsoft Excel license environment (USA).

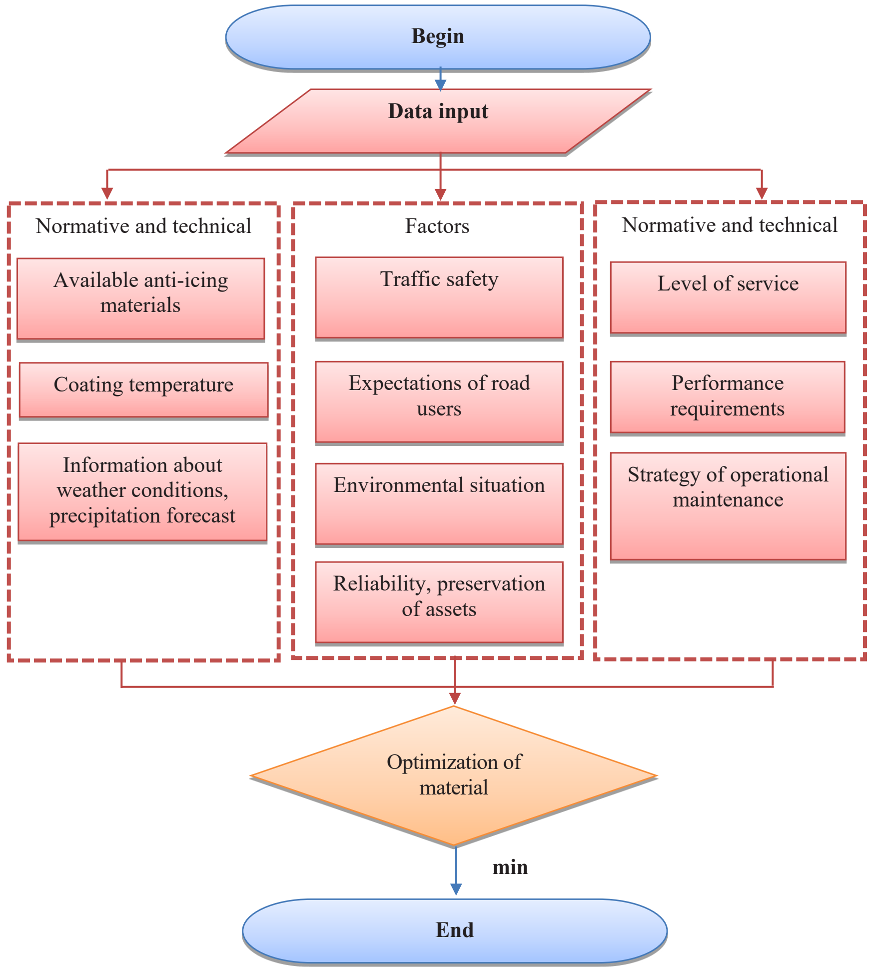

Fig. 2. Algorithm for using the method of optimizing the costs of anti-icing materials during winter road maintenance

3. Results and Discussion

The basic data for the approbation of the proposed method of optimizing the costs of anti-icing materials during the winter maintenance of highways were the data of the city of Kyiv, collected in the period from November 2022 to the end of February 2023 for 12 events. The calculation results are presented in the form of graphic illustrations (Fig. 3–5).

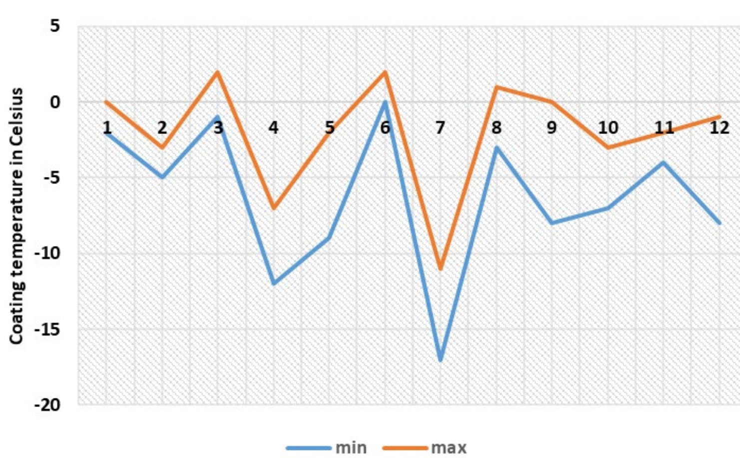

Fig. 3. Measured surface temperature for a section of road clothing

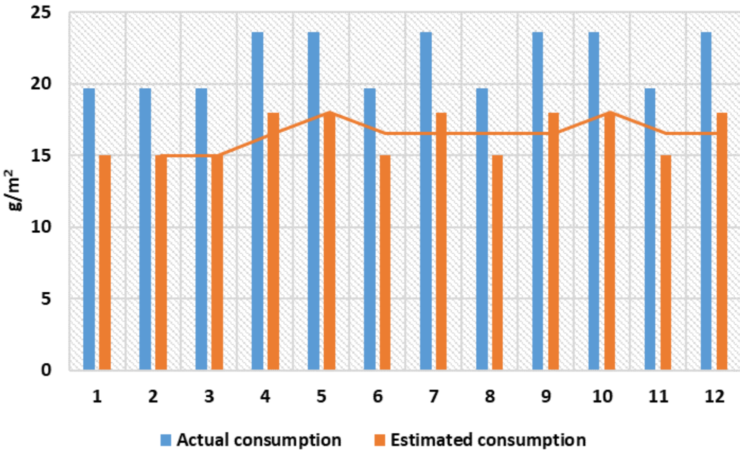

Fig. 4. Actual and estimated consumption of anti-icing materials

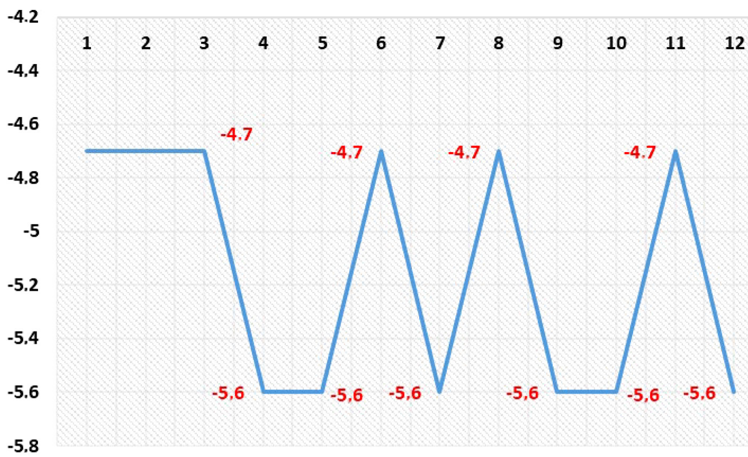

Fig. 5. Analysis of overconsumption of anti-icing materials

According to the graph of the measured temperatures, the anti-icing material – salt – was actually applied by the road organization. Fig. 4 presents the actual consumption of materials and is calculated according to the proposed method per unit of coverage area, taking into account the temperature regime and level of service.

It should be noted that for all events, the actual consumption of materials exceeded the estimated consumption (Fig. 4). To perform a more convenient comparative analysis of actual and estimated data, it is advisable to determine the overconsumption of materials (Fig. 5).

The results of optimizing the costs of anti-icing materials prove that the application of the proposed method in the practical activities of the road organization allows saving materials in the amount of about 23 % (Fig. 5). The limitations of using this method in modern conditions are:
– lack of historical data on winter road maintenance;
– lack of monitoring measures in road organizations that carry out winter maintenance;
– market fluctuations of anti-icing materials in connection with the state of war in Ukraine;
– lack of funds for operational maintenance in general in the state;
– slow introduction of long-term road maintenance contracts [10, 11], etc.

However, it should be noted that the application of the proposed method of optimizing the costs of anti-icing materials in the conditions of martial law in Ukraine is promising from the point of view of saving budgetary funds for winter road maintenance.

In further research, this method will be improved taking into account the economic and social efficiency of using the specified anti-icing materials.

4. Conclusions

According to the research results, based on the analysis of factors influencing the consumption of anti-icing materials, a method of optimizing the consumption of materials during winter maintenance of highways is proposed. A mathematical model of the method is defined, which is based on a binary numbering system, which takes into account the dependence of the use of anti-icing material on the temperature of the coating and the chosen strategy of operational maintenance. An algorithm for the application of the method of optimizing the consumption of anti-icing materials during the winter maintenance of highways has been developed.

Optimization of costs of anti-icing materials was carried out according to the proposed method in the Microsoft Excel license environment (USA). A comparative and comparative analysis of the actual and estimated costs of anti-icing materials according to the data of the city of Kyiv, collected in the period from November 2022 to the end of February 2023 for 12 events, was also carried out. The results of optimizing the consumption of anti-icing materials showed an estimated savings in consumption of materials in the amount of about 23 %. Thus, in the further development of this research, the relative release of reserves and the economic efficiency of the proposed solutions can be calculated.

The results of the study have practical value and can be used to make management decisions regarding winter road maintenance in conditions of financial and resource uncertainty, including those related to circumstances of force majeure, in particular, martial law in Ukraine.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

The manuscript has no associated data.

References

1. Vignisdottir, H. R., Ebrahimi, B., Booto, G. K., O'Born, R., Brattebø, H., Wallbaum, H., Bohne, R. A. (2019). Life cycle assessment of winter road maintenance. *The International Journal of Life Cycle Assessment, 25 (3),* 646–661. doi: https://doi.org/10.1007/s11367-019-01682-y
2. Trenouth, W. R., Gharabaghi, B., Perera, N. (2015). Road salt application planning tool for winter de-icing operations. *Journal*

of Hydrology, 524, 401–410. doi: https://doi.org/10.1016/j.jhydrol.2015.03.004

3. Zítková, J., Hegrová, J., Anděl, P. (2018). Bioindication of road salting impact on Norway spruce (Picea abies). *Transportation Research Part D: Transport and Environment, 59,* 58–67. doi: https://doi.org/10.1016/j.trd.2017.12.010
4. Cui, N., Xie, N., Shi, X.; Shi, X., Fu, L. (Eds.) (2018). A Framework for Life-Cycle Sustainability Assessment of Road Salt Used in Winter Maintenance Operations. *Sustainable Winter Road Operations.* Wiley, 7–22. doi: https://doi.org/10.1002/9781119185161.ch2
5. Maze, T. H. (2009). *Performance Measures for Snow and Ice Control Operations.* doi: https://doi.org/10.17226/23051
6. Malovrh Rebec, K., Turk, J. (2023). Pathway toward Sustainable Winter Road Maintenance (Case Study). *Life Cycle Assessment.* doi: https://doi.org/10.5772/intechopen.110764
7. Fu, L., Trudel, M., Kim, V. (2009). Optimizing winter road maintenance operations under real-time information. *European Journal of Operational Research, 196 (1),* 332–341. doi: https://doi.org/10.1016/j.ejor.2008.03.001
8. Terry, L. G., Conaway, K., Rebar, J., Graettinger, A. J. (2020). Alternative Deicers for Winter Road Maintenance – A Review. W*ater, Air, & Soil Pollution, 231 (8).* doi: https://doi.org/10.1007/s11270-020-04773-x
9. Mbiyana, K. (2018). Winter Road Maintenance Planning-Decision Support Modelling. *Luleå University of Technology. Department of Civil, Environmental and Natural Resources Engineering,* 66.
10. Kharchenko, A., Zaviyskyy, O., Tsybulskyi, V., Zavorotnyi, S. (2021). Development of methods for parameters of long-term contracts optimization for operational road maintenance. *Technology Audit and Production Reserves, 1 (2 (57)),* 49–53. doi: https://doi.org/10.15587/2706-5448.2021.225532
11. Kanin, A., Kharchenko, A., Tsybulskyi, V., Sokolova, N., Shpyh, A. (2022). Construction of a simulation model for substantiating the parameters of long-term road maintenance contracts. *Eastern-European Journal of Enterprise Technologies, 2 (3 (116)),* 33–42. doi: https://doi.org/10.15587/1729-4061.2022.253652

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