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SUBSTANTIATION OF THE FEASIBILITY OF IMPLEMENTING OPTIMIZED GEOMETRIC SOLUTIONS IN THE DESIGN OF METAL GRAIN SILOS

In the current context of restoring Ukraine's agricultural infrastructure, minimizing capital expenditures at the stage of creating grain storage facilities has become a key factor in the financial sustainability of grain business. Metal grain silos (MGS) account for 30-40% of the capital budget of grain storage complexes. However, their design is based on unified geometric parameters that do not consider economic optimization for specific volumes and climatic operating conditions [1].

This approach leads to excessive consumption of structural steel, increased weight of the structure, and a longer payback period for investments. It is important to provide an economic and technological rationale for analytically optimised geometric solutions in the design of metal grain silos in order to reduce capital expenditure for agricultural enterprises without compromising functional and operational characteristics. Which directly aligns with the priorities of engineering and technological support for agricultural production.

The study employs a comprehensive approach that combines methods of differential calculus of functions of several variables with applied economic analysis of the grain storage facility's life cycle. The underlying hypothesis was that minimizing the external surface area of a silo while maintaining a constant useful volume directly translates into reduced manufacturing costs.

To solve the conditional optimization problem, the Lagrange multiplier method was applied, where the objective function is the total surface area of a cylindrical body with a conical roof and conical bottom, and the constraint is a fixed useful volume $V = \pi r^2 h$. The roof slope angle $\alpha = 15^\circ \div 30^\circ$, bottom slope angle $\beta = 45^\circ \div 60^\circ$ were assumed constant, as they are determined by climatic loads (snow, wind, precipitation) and physico-mechanical properties of grain (angle of repose, friction coefficient) [2].

Analytical solution of the system of equations yielded a universal ratio for rational parameters: $h/r = \sec \alpha - \sec \beta$. It was proven that the second differential of the objective function is positive definite for all $r > 0$, guaranteeing a global minimum of surface area and, consequently, minimization of the structure's material intensity.

Practical modeling for typical volumes of $110 - 482 \text{ m}^3$ demonstrated that implementing the obtained analytical ratio allows reducing structural steel consumption by $8 \div 12 \%$ compared to typical industrial solutions, which often prioritize modular unification over individual optimization [3]. In monetary terms, for a 300 m^3 silo, this means direct savings of UAH 45-68 thousand at the stage of steel sheet procurement and cutting alone. However, the economic effect is multiplicative: a $5 \div 7 \%$ reduction in structural weight automatically decreases foundation loads, reduces transportation costs for sectional delivery, enables the use of less powerful lifting equipment, and accelerates installation work by $10 \div 14 \%$. This positively impacts the commissioning timeline and investment return dynamics, which is critically important for small and medium-sized agricultural enterprises operating under limited access to long-term financing.

Verification of results was conducted through comparative analysis of catalog data from domestic and European manufacturers, including LLC «LUBNYMASH», «KMZ Industries», «Silos Spain». It was established that approximately 35% of serial models have geometric parameter deviations from the theoretical optimum within $\leq 10\%$, confirming partial intuitive implementation of the material economy principle in modern engineering practice. However, the vast majority of models (over 60%) exhibit deviations $> 10 \%$, which is not due to technical infeasibility but rather a combination of market and production constraints: fixed height of corrugated rings for simplified serial production, orientation toward farmer demands for rapid gravity unloading, necessity of elevated support structures for heavy machinery access, and market differentiation by price segments. These factors do not negate the economic potential of optimization but indicate the need for a flexible design approach: applying the analytical model as a baseline filter at the conceptual stage, followed by adaptation to the functional requirements of a specific facility.

The established theoretical ratio can be embedded into manufacturers' CAD/PLM systems as a tool for automated preliminary assessment of parameter rationality. It is enabling a balance between economic efficiency, structural reliability, and market adaptability. For agricultural enterprises, implementing such solutions means reducing capital expenditures, shortening the payback period of grain storage investments, and enhancing overall financial resilience in the post-war recovery context. The obtained results confirm the feasibility of integrating analytical methods of geometric optimization into the decision-making process for engineering and economic solutions in MGS design.

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