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COMBINED OPTIMIZATION OF COUNTERACTING ENEMY AMPHIBIOUS OPERATIONS IN COMPUTER MODELING

The object of research is an integrated coastal defense system using mine barriers and artillery batteries. The research was conducted for a typical landing force and uniform mining within the fairway.

Among the most challenging issues are accounting for heterogeneous weapons and uncertainties in the combat environment. Another challenge is choosing between the speed of completing the operation and the cost of resources.

The paper presents a combined model for countering amphibious assaults, which combines the effects of sea mine barriers and artillery fire in a single scale of relative explosive effectiveness. This allows for the optimization of resource and time expenditure. Additionally, robustness to disturbances due to the loss of mines and guns ($\Delta m, \Delta g$) is taken into account.

The research employs: standardization of ammunition nomenclature, Markov model of shelling, probabilistic model of detonation, and two-criterion optimization.

A unified model of combined optimization (ρ, G) in a common metric was developed. The operation was simulated in different modes. Robust corrections were introduced to the effective number of mines and guns in case of disturbances. For the practical selection of parameters, the ε -constraint method was applied, and tactical modes of use were outlined.

The results of modelling the response time of the operation T_{tot} and resource costs S were obtained. T_{tot} depends more on G and ρ (minimum 26 minutes) than on S , which has a dominant influence to a greater extent than ρ (minimum 80 tons). This is due to the fact that as G increases, the operation time is reduced due to parallelism. Meanwhile, an increase in ρ will lead to a high probability of disruption, reducing the need for shells.

Accordingly, the proposed model enables rapid selection of parameters to meet prescribed time thresholds and risks of enemy breakthrough.

Keywords: combined optimization, counter-amphibious operation, artillery support, minefield modeling, resource minimization.

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1. Introduction

The problem of countering marine landings involves not only the selection of the "best" weapon, but also the coordinated development of several subsystems with different mechanisms of action and time dynamics. In a typical scenario, minefields are designed to reduce the size and pace of the landing, and artillery must ensure the completion of the combat operation within a given time slot. Accordingly, the problem is correctly formulated as a joint optimization of two solution variables – minefield density ρ and number of guns G – taking into account operational time constraints and minimizing resource costs on an overall scale. Despite mature, independent approaches to mine countermeasures and artillery fire control, this complex formulation remains understudied in the open literature. The paper [1] is devoted to multi-criteria planning of mine countermeasure missions. It is noted that this problem is complex, requires planning and searching for alternative routes, and the algorithm is designed to provide the commander with several options for the action plan. In [2] analyses modern defense operations, defines the role of engineering obstacles and offers recommendations for the development of specialized software for the calculation and planning of engineering obstacle systems, based on NATO experience. The paper [3] presents the modern experience of

using mines in conflicts (from the 1950s to the present), noting that mines remain an important factor in balancing the forces of the parties and neutralizing the enemy's advantage. The article considers the specifics of modern mine warfare, in particular the use of small groups of mines, remote mining and the shortcomings of mine clearance systems.

The idea emerged to use Markov models to sequentially estimate the duration of "completion" of objectives and the number of rounds required, as well as approaches to quantitatively assess the impact of a minefield as a conditional probability of detonation for a given field density. This yields a cross-system optimization consistent with a time constraint. Study [4] describes tactical methods for using cannons against landing forces in a virtual environment, including optimization of the number of shells and the moment of opening fire. In [5] describes a discrete Markov model that simulates firing errors, it proposes excluding "ineffective" guns based on the probability of misses to increase firing efficiency. In turn, [6] develops a technology for assessing the level of wear on artillery barrels based on acoustic signals using a binary SVM classifier, and high recognition accuracy is achieved, which is more useful for selecting a method for diagnosing the condition of guns.

Classical works on analytical assessment of damage during minefield transit laid the foundations for detonation probability and for transitioning to the expected number of "surviving" targets. The model

presented in [7] calculates survival functions when passing through minefields with clusters, taking into account detection, neutralization, and the probability of detonation or miss. On the other hand, the model in [8] is designed to assess minefields, taking into account the number of mine detonations based on known mine coordinates and ship routes. The approximation is based on the assumption that a ship's approach to a mine describes a heterogeneous Poisson process. This is useful for assessing the effectiveness of mine barriers. Cressie's and Collins's approach demonstrates the importance of the field's spatial structure for local indicators of association and the real effectiveness of barriers [9]. These results support parameterizing density ρ and using expectations by target types in the minefield block.

In contrast, [10] discusses design principles for artillery accuracy. It develops kinematic and dynamic equations for shells, analyses errors and sensitivity, and proposes gun design principles. However, it does not provide formulas for the number of volleys or consider fire planning. In [11] builds physical models of ballistic and muzzle sound waves during an artillery shot. This was done in order to separate these waves and estimate barrel wear based on acoustic signals, which confirms the possibility of non-invasive diagnostics of the gun condition. Thus, the analysis of the "shoot and run" tactic determines the time windows and risks of counter-battery combat, i. e. the same constraints formalized in the model as ε -time constraints [12]. However, [13] discusses the evolution of artillery application rules, analyses historical principles, and proposes new rules to improve efficiency, while [14] proposes a method for assessing firing accuracy during exercises. Therefore, it can be determined that the lack of research that combines these subsystems into a single optimization of resource pooling emphasizes the novelty of our approach: the joint choice of ρ and G to minimize the TNT equivalent, taking into account time constraints and losses.

The aim of research is to develop a combined coastal defense model that integrates the installation of minefields and subsequent artillery strikes. It is also necessary to determine parameters such as mine density and number of guns. This will minimize the total TNT equivalent of resources expended while adhering to the time constraints of the operation.

The object of research is an integrated coastal defense system using mine barriers and artillery batteries. The system is examined in terms of operational time efficiency and resource expenditure, while accounting for combat-environment uncertainties and attrition of assets.

For a given composition of the landing wave, find a combination of countermeasures that minimizes the total mass of explosives and satisfies the time constraint for completing the operation. For the problem as described, it is necessary to:

- determine the structure of the mathematical model and the variables included in the description;
- conduct simulation and get dependencies of the operation time and TNT-consumption on the mining density and number of defending guns;

- determine the optimal tactical methods and expected operation time based on two-criteria optimization.

2. Materials and Methods

The following scientific methods were used in the research:

1. Method of analysis for selecting a range of ammunition and mines, coordinating their characteristics on a common scale of explosive efficiency, and forming input parameters and tables. Energy unification of resources (TNT equivalent) was used for the joint calculation of the consumption of mines and artillery ammunition in a single indicator, which allows comparing heterogeneous means of destruction.
2. Classification method for grouping target types by effective damage area and other parameters, which ensures the correct setting of probabilities and damage requirements for ship classes. By analogy with [4], each target type requires a different amount of destructive potential.
3. Mathematical modeling to estimate the probability of detonation and to determine the time of destruction of each target (time discrete – one series of shots). Probabilistic modeling of the minefield is used to assess the effectiveness of mining within the fairway. The Markov model describes the sequential states of "firing – hitting – completion" and is parameterized by the number of barrels and the rate of fire.
4. Optimization methods, in particular two-criteria optimization using the ε -constraint method, to minimize total costs in TNT equivalent while adhering to the operation time threshold, generate a set of Pareto-optimal combinations (G, ρ) under specified constraints.
5. Sensitivity and robustness analysis to account for disturbances due to resource losses ($\Delta m, \Delta g$) by switching to "effective" quantities and assessing the impact on operation time and costs.
6. Simulation modeling on a parametric grid in the Scilab[®] environment to construct response surfaces and corresponding heat maps, which are used for tactical mode selection.

3. Results and Discussion

3.1. Structure and parameters of the mathematical model

Tables 1, 2 are considered for modeling resource use. Switching to TNT simplifies production, but in TNT-equivalent terms, it yields $\approx 40\%$ less explosive energy per round [15] (RE/Relative Effectiveness – the coefficient of a given explosive's effectiveness relative to TNT).

The conversion to TNT-equivalent is calculated by the following formula

$$M_{TNT, i} = m_i \cdot RE_i, \tag{1}$$

where m_i – the physical charge mass of a specific mine/projectile.

Table 1
Comparative characteristics of projectiles for the "Giatsint" artillery system (2A36/2S5 gun, 152 mm caliber)

| Projectile | Filler | Charge mass, kg | RE | TNT-eq., kg |
|-----------------|------------------------------------|-----------------|------|-------------|
| 3OF45 (3OΦ45) | A-IX-2 (73% RDX + 23% Al + 4% wax) | 7.65 | 1.54 | 11.8 |
| OF-25T (OΦ-25T) | Cast TNT | 7.00 | 1.00 | 7.0 |

Table 2
Comparative characteristics of moored naval mines suitable for mining the fairway of Odesa Oblast

| Mine (class) | Detonation type | Explosive mass, kg | Filler | RE | TNT, kg |
|------------------------------|--------------------|--------------------|------------------------------|-------------|----------|
| YARM (ЯРМ – anti-amphibious) | contact | 3 | TNT | 1.00 | 3 |
| R-421-75 (contact/automatic) | contact/inertial | 80 | TNT | 1.00 | 80 |
| UDM-1 (YARM modification) | induction/contact | 135 | Hexal (TNT + RDX + Al) | 1.35 | 182 |
| TM-72/TM-89 (bottom-moored) | magnetic/induction | 9.5 | TG-40/60 (TNT 40% + RDX 60%) | 1.20 ± 0.05 | 11 ± 0.5 |

To compute the required number of mines, formula is applied

$$N_{mine} = \rho \cdot S_f, \quad (2)$$

where ρ – mine density, pcs/km² (decision variable); S_f – area of the minefield, km².

In [16], Bayesian networks are used to assess the effectiveness of modern mine detection and to create a minefield risk map. However, in the current research, it is proposed to consider the probability of ship detonation assumed under a uniform distribution of mine barriers along the fairway

$$P_{hit,c} = 1 - (1 - P_i)^{N_k}. \quad (3)$$

Mathematical expectation of the number of ships remaining after transiting the mine barriers

$$E_{surv,c} = k_c \cdot [1 - P_{hit,c}(\rho)], \quad (4)$$

where k_c – the initial number of ships of type c .

To calculate the number of shells that may be required for the artillery assets, formula is applied

$$N_{shell} = \sum_c E_{surv,c} \cdot n_{ser,c} \cdot n_{shot/ser} \cdot G, \quad (5)$$

where $n_{ser,c}$ – series of shots per one ship to achieve $P_{kill} \geq 0.95$; $n_{shot/ser}$ – shells per series, 2 minutes of fire; G – number of guns (decision variable).

So the total TNT-equivalent equals

$$S_{TNT, total}(\rho, G) = \underbrace{\sum_j N_j \cdot m_j \cdot RE_j}_{mines} + \underbrace{N_{shell} \cdot m_{shell} \cdot RE_{shell}}_{artillery}. \quad (6)$$

And the first objective function accordingly

$$S_{TNT, total}(\rho, G) \rightarrow \min_{\rho, G}. \quad (7)$$

For a given composition of the landing force, it's formulated the modeling of such a combination of mine density ρ (pcs/km²) and number of guns G that minimizes the total mass of explosives

$$S = N_{mine} \cdot e_{mine} + N_{shell} \cdot e_{shell}, \quad (8)$$

where e_{mine} , e_{shell} – the explosive masses in one mine/one shell, and the expected number of shells

$$N_{mine} = \rho \cdot S_{field} - N_{shell}. \quad (9)$$

Artillery block (Markov submodel), where $n_{ser,c}$ – the number of shot series per ship c for $P_{kill} \geq 0.95$

$$n_{shot/ser} = 2 \cdot rate_{fire}. \quad (10)$$

Subject to the constraints

$$\begin{aligned} T_{destroy}(\rho, G) &\leq T_{max}, \\ P_{residual hit}(\rho, G) &\leq P_{thresh}, \end{aligned} \quad (11)$$

where $T_{destroy}$ – total time to neutralize the wave (taking into account artillery fire and time saved due to unsuccessful sweeping by minesweepers); $P_{residual hit}$ – probability that at least one ship will break through.

Stochastic disturbances and robustness or empirical "sensitivity" coefficients of influence

$$\begin{aligned} \rho_{eff} &= \rho(1 - \Delta m), \\ G_{eff} &= [G \cdot (1 - \Delta g)], \\ \Delta g, \Delta m &\in [0, 1]. \end{aligned} \quad (12)$$

The time required by a single gun to likely destroy a ship c is computed by

$$T_c^{(1)} = \frac{n_{ser,c} \cdot n_{shot/ser}}{rate_{fire}}. \quad (13)$$

Expected time saving due to mines (14) – the firing time against surviving ships

$$T_{saved} = \frac{1}{G_{eff}} \cdot \sum_c k_c \cdot P_{hit,c} \cdot T_c^{(1)}, \quad (14)$$

where the time that would be needed by artillery if no ship detonated is

$$T_{full} = \frac{1}{G_{eff}} \cdot \sum_c k_c \cdot T_c^{(1)}. \quad (15)$$

Thus, the actual time of the artillery operation (16) will include the total firing time

$$T_{total} = T_{full} - T_{saved}. \quad (16)$$

From (13) and (14) it follows that the expected time of the counter-landing operation equals

$$T_{saved} = \frac{1}{G_{eff}} \cdot \sum_c k_c \cdot (1 - P_{hit,c}) \cdot T_c^{(1)}. \quad (17)$$

Two objective indicators are obtained: (17) and (18), where (18) is the total TNT-equivalent of resources employed

$$\begin{aligned} S_{TNT, total}(\rho, G, \Delta m, \Delta g) &= \\ &= \underbrace{N_{mine}^{eff} \cdot m_{mine} \cdot RE_{mine}}_{mines} + \underbrace{N_{shell} \cdot m_{shell} \cdot RE_{shell}}_{artillery}. \end{aligned} \quad (18)$$

The described bi-parameter optimization accounting for disturbances

$$\min_{\rho, G} \{ E_{\Delta m, \Delta g} [S], E_{\Delta m, \Delta g} [T_{total}] \}, \quad (19)$$

where the expectation is taken over the distributions of Δm , Δg with random disturbances: Δm – random reduction in the effective number of mines, Δg – random destruction of guns, which affect the "effective" number of mines (20) and guns (21):

$$N_{mine}^{eff} = \rho \cdot S_f (1 - \Delta m), \quad (20)$$

$$G^{eff} = G(1 - \Delta g). \quad (21)$$

Functions depending only on mine density ρ (22) and (23):

$$P_{hit,c}(\rho) = 1 - \exp[-\rho \cdot A_c \cdot P_i], \quad (22)$$

$$\begin{aligned} S(\rho) &= \rho \cdot S_f \cdot \underbrace{m_{mine} \cdot RE_{mine}}_{mines} + \\ &+ \underbrace{\sum_c k_c \cdot [1 - P_{hit,c}(\rho)] \cdot n_{ser,c} \cdot n_{shot/ser} \cdot m_{shell} \cdot RE_{shell}}_{artillery}, \end{aligned} \quad (23)$$

where A_k – the effective target area.

For optimization, the ε -constraint method is applied. The permissible operation duration is set (up to two hours), $\varepsilon_t = 120$ minutes, $\varepsilon_s = 52$ guns. Formally, the selection can be expressed as

$$\begin{aligned} \min_{\rho, \text{guns}} S & \text{ subject to } T_{\text{tot}} \leq \varepsilon_T, \\ \min_{\rho, \text{guns}} T_{\text{tot}} & \text{ subject to } S \leq \varepsilon_S, \end{aligned} \quad (24)$$

where $\varepsilon_T, \varepsilon_S$ are tactical thresholds.

3.2. Simulation and results

An assault wave of targets $\Gamma = [2, 6, 4, 6]$ was considered and simulated for ship types [DK1171, DK775, MTSh, DKa]. Artillery used is the 152-mm "Giatsint" self-propelled gun. The minefield is considered as a uniform distribution with density $\rho \in [50, 300]$ units per sq. km. For each ship type, a "heavy" submodel (Markov chains) is used with estimates of the time to destroy $T_k^{(1)}$ a single object and the required number of shot series $n_k^{(1)}$ for a baseline of 18 guns.

The probability of detonation in the field was defined as $P_{hit, k} = 1 - (1 - P_i)^{N_k}$ with $N_k \propto \rho \cdot A_k$, where A_k is the effective target area. The total operation time (Fig. 1) and TNT equivalent (Fig. 2) were computed in terms of expected values. Sensitivity to disturbances Δm (mine losses) and Δg (gun losses) was also examined.

Full simulation was performed for all $G \in [18, 52], \rho \in [50, 300]$, with steps of 1 and 25, respectively.

Operation time: The surface $T_{tot}(G, \rho)$ (Fig. 1) decreases monotonically along both axes: more barrels (parallelization) and denser minefield (more detonations) lead to a shorter duration. The reduction in G recoil is noticeable after 30–35 barrels: every additional 10–15 barrels reduces the duration. Representative items:

- minimum: 25.8 minutes at $G = 52, \rho = 300$;
- "typical median" over the grid: 79.8 minutes at $G \approx 27, \rho \approx 125$;
- worst edge within the stated range $\rho \approx 160$ minutes with $G = 1, \rho = 50$.

Explosive TNT consumption: The surface $S(G, \rho)$ (Fig. 2) is most sensitive to ρ : with increasing mine density, TNT consumption decreases due to a larger fraction of detonating targets and a lower shell consumption. Along the G axis, S is almost flat, which is consistent with the model (the number of shots fired at the "survivors" is determined by the wave composition, not the parallelism of the fire). Representative items:

- minimum: 79.7 thousand kg at $\rho = 300$ (almost independent of G);
- typical mean values: 1.3×10^5 kg at $\rho \approx 200$;

- worse values: 2.0×10^5 kg for sparse mining ($\rho \approx 50$), when most destructive potential falls on artillery.

Trade-offs and limitations for ε : For practical information, see the following three tactical modes:

- speed priority ($G \geq 40, \rho \geq 250$): 25–40 minutes runtime, 80–95 t TNT;
- balanced (G is 24 to 32 guns, ρ is from 150 to 200 units/km²): 60–80 minutes runtime, 110–120 t TNT;
- minimum TNT ($\rho = 300$ units/km² and $G = 0$): 79.7 t, but runtime revised 2 hours ago.

3.3. Optimal parameter selection and tactical guidelines

The tactical mode of weight gain and balance (compromise) ($G = 32, \rho = 175$) was used for the analysis, and the simulation was performed for $\Delta m, \Delta g \in [0, 0.50\%]$ (Fig. 3, 4).

Extreme points:

- minimal time for $\Delta m = \Delta g = 0$ is 58–60 minutes; inner plating 109–110 t (as expected);
- median values (according to the $\Delta m \times \Delta g$ matrix): 90–105 minutes with Δm between 30% and 35% and Δg between 20% and 30%; TNT equivalent at these points is 125–133 t;
- maximal weight mass determined by close to half of resource content: $\Delta m \approx 50\%, \Delta g \approx 50\%$: 150–160 minutes, TNT equivalent 140–145 t, indicating the likelihood of natural combat after landing.

Relative influence of Δg and Δm . At the same loss rate, g decreases faster than m . More information on the following:

- 10% increase in Δg additional time for 12–15 hours;
- 10% increasing Δm increases the time by 5–7 minutes.

Robustness settings: to get $T_{tot} < 120$ minutes with expected losses for Δm and Δg about 20%, it's required to increase ρ up to 200 mines per km² or to increase G up to 36 guns. For TNT power less than 120 t with Δm about 30%, increasing minutes is expected.

Tactical choice: according to Pareto efficiency and sensitivity to disturbances, two practical configurations are defined:

- for tight time constraints (so for ε_T is about 45 minutes) it probably will have G about 52 guns and ρ about 300 mines per km², which provides 25 minutes with TNT of about 95 t and allows an acceptable tolerance for Δm and Δg about 20%;
- for balanced in economy and fast regimes ($\varepsilon_T \leq 90$ minutes): G will be about 24 guns and ρ is about 175 mines/km², which corresponds to approximately 60 minutes at 110 t, with reduced sensitivity to Δg with sufficient parallel shooting effect.

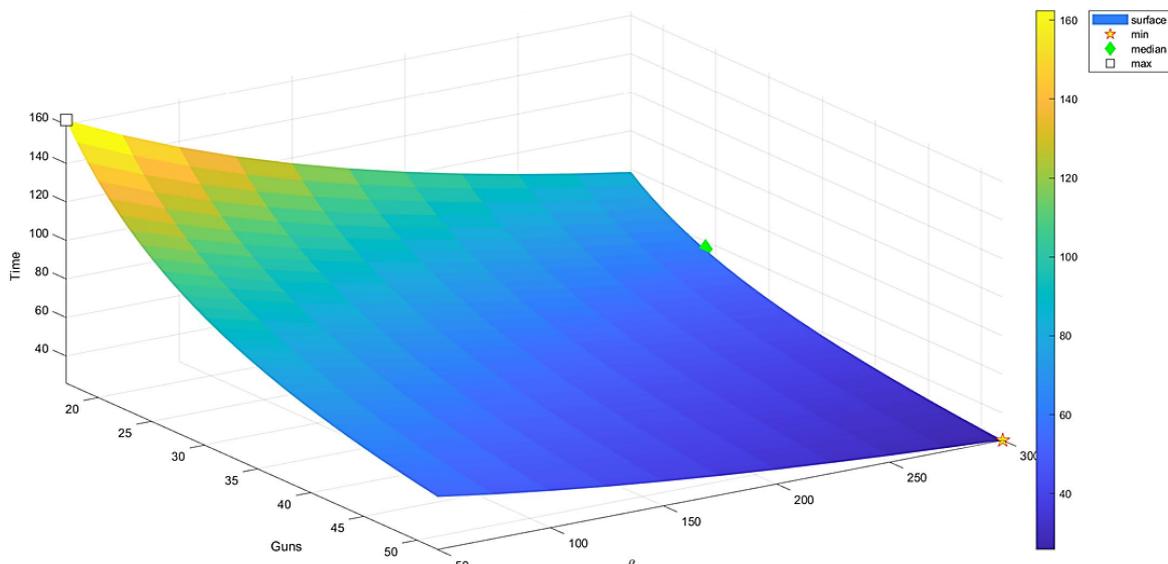


Fig. 1. Simulation result for time expenditure in a standard operation without disturbances ($\Delta g = \Delta m = 0\%$)

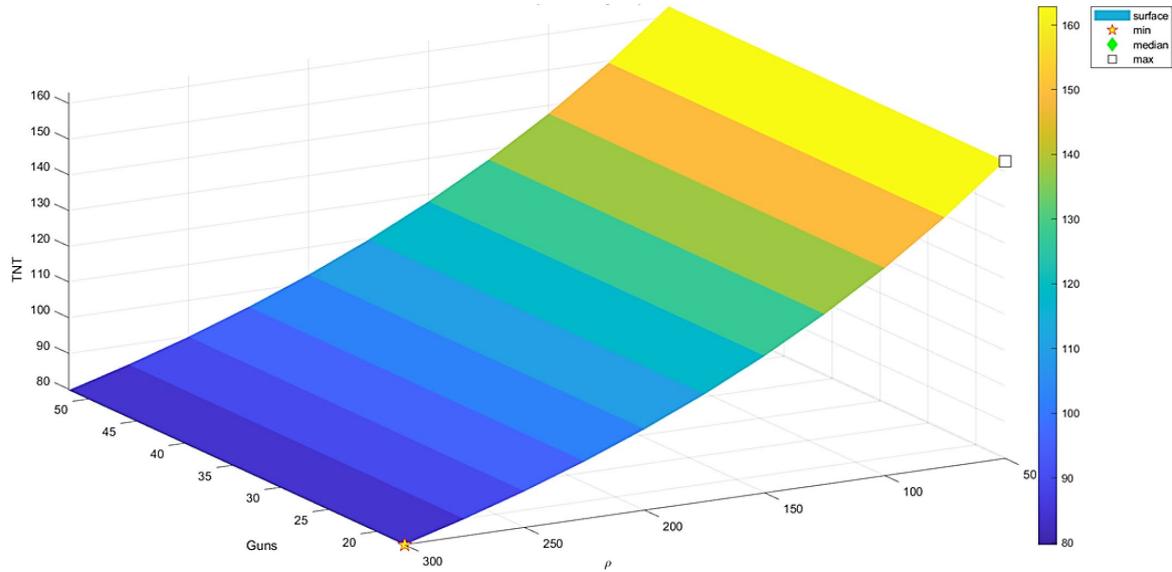


Fig. 2. TNT equivalent cost simulation result for a standard, undisturbed operation ($\Delta g = \Delta m = 0\%$)

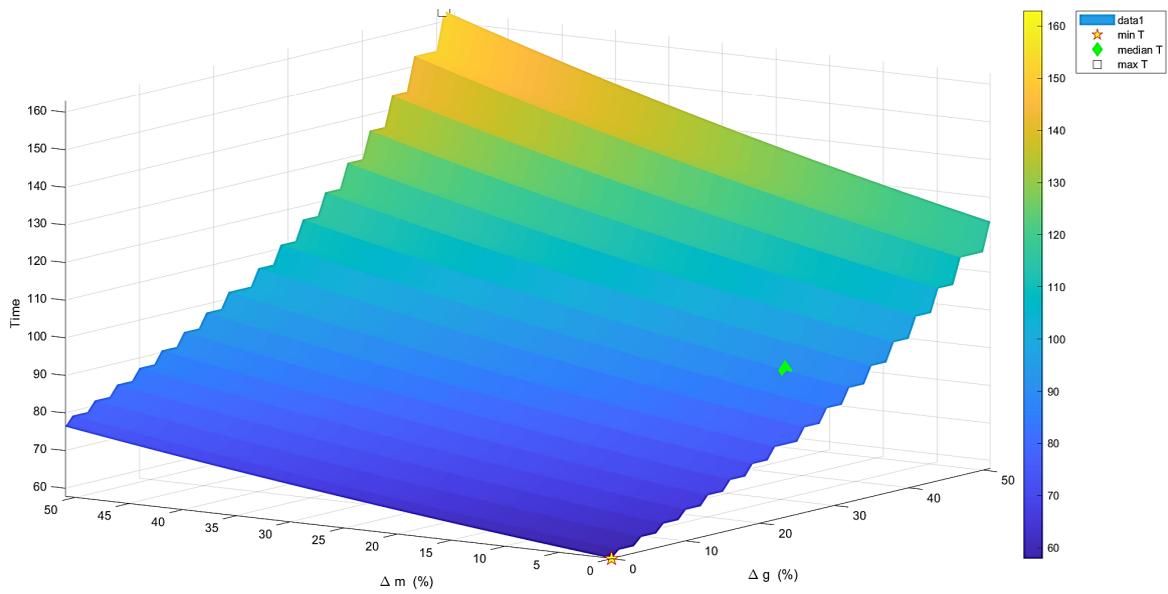


Fig. 3. Simulation of time consumption in a compromise tactical mode with the variables Δg and Δm

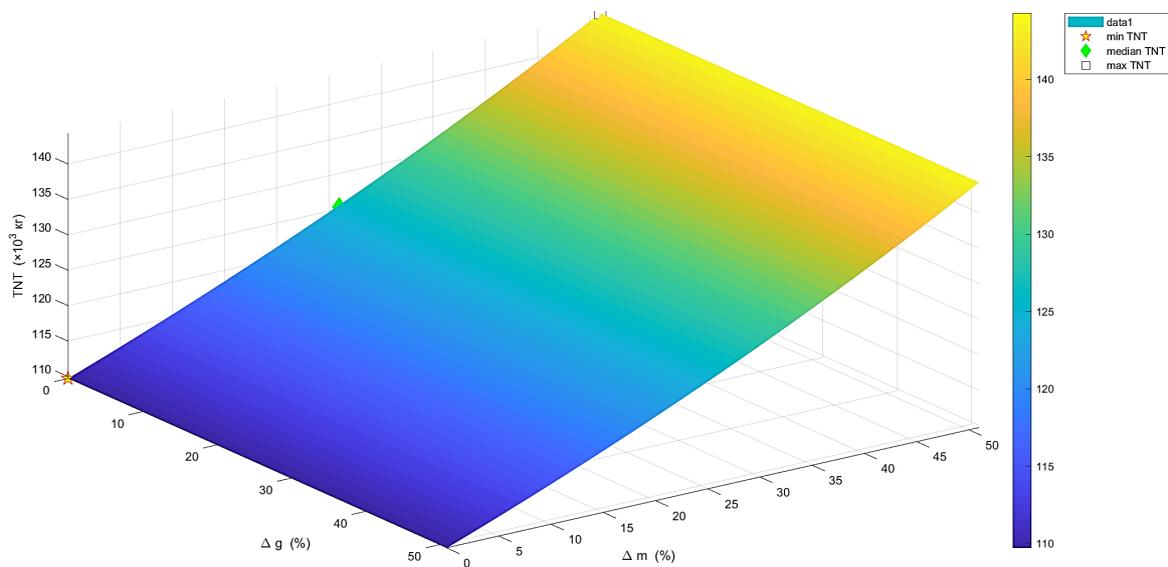


Fig. 4. Simulation of resource consumption in a three-dimensional equilibrium and favorable tactical mode with the variables Δg and Δm

3.4. Discussion

The results in sections 3.2 and 3.3 were obtained based on the simulation of the model described in section 3.1, where the problem boils down to choosing two controllable parameters: the density of the minefield and the number of artillery barrels. In Fig. 1, the dependence of T_{tot} decreases for both parameters: an increase in G reduces the time due to parallel fire, and an increase in ρ increases the probability of detonation and reduces the number of targets requiring artillery strikes. Fig. 2 shows that S depends much more on ρ than on G : the density of the minefield determines the expected proportion of neutralized targets and, accordingly, the scale of total costs in equivalent terms, while G mainly affects the duration rather than the amount of costs. Thus, these results can be interpreted as follows: G is critical for meeting time requirements, while ρ is critical for saving resources. The described model and its simulation reproduce the procedure for selecting parameters for forecasting coastal protection, taking into account certain time and resource constraints (depending on the needs of the combat situation). Therefore, it is possible to choose between T_{tot} and S , as described in section 3.3. As a result, the parameters G and ρ will be planned for the operation not intuitively, but according to one of the modes: either speed priority (more G and possibly ρ), or strict economy mode due to lack of resources (control of T_{tot} by increasing ρ and reducing guns), or a compromise optimal mode (average value of G and ρ).

Practical significance: the obtained thermal maps T_{tot} and S , together with ε -constraints (taking into account the limited duration of the operation and/or the cost of ammunition), make it possible to determine the necessary tactical method and choice of pair (guns, mines):

- planning coastal defense resources (artillery and mine placement) for specific sea lanes with an understanding of the enemy's possible attack algorithm;
- preparing methodological guidelines in the form of tables/heat maps of risks and advantages for planning at headquarters and operational regrouping in case of sudden system disturbances;
- comparison of tactical methods between fast, economical and optimal counter-amphibious operation plans, in accordance with considerations and strategic planning;
- improvement of ammunition logistics through stockpiling in the form of sea mine barriers, which can significantly reduce the need for timely delivery of shells and reduce the risks of supply routes.

Research limitations and requirements: within the framework of counter-landing operations when crossing rivers, straits, canals and other water bodies, the model described with tactical methods may have irrelevant meanings. The simulation results are also based on the following assumptions:

- mine barriers are placed evenly along the fairway;
- personnel and landing attack schedules are based on empirical experience from previous enemy operations and need to be recalculated for other theatre of operations scenarios;
- the explosion of an engineering munition within the model is always considered successful when the enemy ship is within the mine's radius of action;
- the optimization task is based on mathematical expectations;
- the Markov chain does not take into account transport delays, weather conditions, counter-battery fire from enemy fire support ships, or disturbances from the operation of guns: barrel overheating, unpredictable breakdowns, and personnel casualties;
- simulation modelling was performed for 152 mm caliber guns and a traditional artillery battery composition, so for other calibers and battery compositions, the model requires additional calculations;
- the underwater blast wave effect for different types of mines and the hull strength of some types of ships may vary.

The following data are required for practical implementation:

- geospatial data (if a sector other than the selected prototype is to be modelled) and support for uneven mining patterns;

- up-to-date intelligence on the composition of the wave, the pace, and means of enemy minesweeping;
- ballistic tables for existing batteries and detonator settings;
- display of stocks in TNT equivalent for the actual nomenclature.

Prospects for further research: further development of the model should include explicit demining dynamics, enemy adaptation (mixed strategy games), and joint firepower, which will improve accuracy and suitability for real-world command and control tools. There is also potential for institutionalizing the proposed model as an integrated research platform that formalizes inputs on enemy composition and own resources. This solution can generate a set of probabilistic event scenarios and perform comparative evaluations using a common metric with theoretical guarantees of performance and optimality. This will allow the use of experimental design methodology, Bayesian calibration, and cross-validation of models to obtain reproducible results and strengthen the theoretical foundations of combined (ρ , G) optimization for uncertain G .

4. Conclusions

1. A single combined formula with two decision variables (ρ , G) is developed, in which the different costs (mines and artillery ammunition) are reduced to a common equivalent TNT scale. A probabilistic minefield submodel estimates detonation, a Markov model provides the completion and firing times, and a two-criteria optimization is solved using the ε -constraint method with fatigue resistance (Δm , Δg). The model provides a common language for comparing effects, a transparent mechanism for choosing time constraints and breakthrough risk, and a reproducible basis for personnel decision-making.

2. An exhaustive grid was performed for $G \in [18, 52]$ and $\rho \in [50, 300]$ (steps 1 and 25). The response surfaces T_{tot} and S show that the firing time decreases monotonically with both G and ρ , with a noticeable decrease in recoil after ~30–35 barrels. S is determined mainly by ρ and remains almost constant with G . Increasing G increases the parallelism of the fire and shortens the firing time, while increasing ρ increases the probability of detonation from TNT consumption to Δg and Δm .

3. Recommended tactical modes: speed priority ($G \geq 40$, $\rho \geq 250$), balanced ($G \in [24, 32]$, $\rho \in [150, 200]$) and minimum TNT ($\rho = 300$, $G \rightarrow 0$). Reliable settings: To maintain $S \lesssim 120$ t below $\Delta m \approx 30\%$, increasing the bore to $\rho \approx 200$ is critical to control the barrel dwell time, since Δg has a greater effect on T_{tot} . A practical selection procedure is the ε -constraint method, which involves a one-dimensional search for ρ with fixed G (or vice versa) in predictable ranges for m and g . The balance between velocity and explosive consumption is determined by the parameter (ρ , G): for compressed windows, the gun reserve should be maintained; for active demining, ρ should be increased. Both levers have predictable effects and can be quickly adjusted.

Conflict of interest

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

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Data availability

Data will be provided upon reasonable request.

Use of artificial intelligence

The authors declare the use of generative AI in the research and preparation of the manuscript. Tasks delegated to generative AI tools under full human supervision: Grammar editing.

Generative AI tool used: Grammarly™ Pro and LanguageTool™.

The authors bear full responsibility for the final manuscript. Generative AI tools are not credited and are not responsible for the final results.

Declaration submitted by: Maksym Grishyn.

Authors' contributions

Maksym Maksymov: Terminology, Methodology, Validation, Formal analysis, Writing – review and editing, Supervision, Project administration; **Maksym Grishyn:** Conceptualization, Methodology, Software, Investigation, Writing – original draft; **Oleksii Neizhpapa:** Terminology, Conceptualization, Validation, Investigation, Resources, Data curation, Writing – review and editing.

References

1. Trail, C. D., Schmiedekamp, M. D., Phoha, S., Sustersic, J. P. (2013). Multiobjective planning for naval mine counter measures missions. *International Journal of Operational Research*, 16 (1), 113. <https://doi.org/10.1504/ijor.2013.050626>
2. Ftemov, Yu. (2021). Recommendations for creating specialized software for calculation the engineering barrier systems. *Systems of Arms and Military Equipment*, 1 (65), 131–136. <https://doi.org/10.30748/soivt.2021.65.19>
3. Neroba, V. (2019). The role of mining weapons in the modern wars and border conflicts. *Collection of scientific works of the National Academy of the State Border Guard Service of Ukraine. Series: Military and Technical Sciences*, 81 (3), 155–171. <https://doi.org/10.32453/3v81i3.444>
4. Grishyn, M., Maksymova, O., Kirkopulo, K., Klymchuk, O. (2025). Development of methods of artillery control for suppression of an enemy amphibious operation in video game simulations. *Technology Audit and Production Reserves*, 1 (2 (81)), 26–33. <https://doi.org/10.15587/2706-5448.2025.321797>
5. Boltenkov, V., Brunetkin, O., Dobrynin, Y., Maksymova, O., Kuzmenko, V., Gultsov, P. et al. (2021). Devising a method for improving the efficiency of artillery shooting based on the Markov model. *Eastern-European Journal of Enterprise Technologies*, 6 (3 (114)), 6–17. <https://doi.org/10.15587/1729-4061.2021.245854>
6. Dobrynin, Y. V., Boltenkov, V. O., Maksymov, M. V. (2020). Information technology for automated assessment of the artillery barrels wear based on SVM classifier. *Applied Aspects of Information Technology*, 3 (3), 117–132. <https://doi.org/10.15276/aait.03.2020.1>
7. Zacks, S. (1979). Survival distributions in crossing fields containing clusters of mines with possible detection and uncertain activation or kill. *Naval Research Logistics Quarterly*, 26 (3), 423–435. <https://doi.org/10.1002/nav.3800260306>
8. Mjeldel, K. M. (1977). An analytical minefield evaluation model without space averages. *Naval Research Logistics Quarterly*, 24 (4), 639–650. <https://doi.org/10.1002/nav.3800240411>
9. Cressie, N., Collins, L. B. (2001). Patterns in spatial point locations: Local indicators of spatial association in a minefield with clutter. *Naval Research Logistics*, 48 (5), 333–347. <https://doi.org/10.1002/nav.1022>
10. Qian, L., Chen, G., Tong, M., Tang, J. (2022). General design principle of artillery for firing accuracy. *Defence Technology*, 18 (12), 2125–2140. <https://doi.org/10.1016/j.dt.2022.09.001>
11. Dobrynin, Y., Volkov, V., Maksymov, M., Boltenkov, V. (2020). Development of physical models for the formation of acoustic waves at artillery shots and study of the possibility of separate registration of waves of various types. *Eastern-European Journal of Enterprise Technologies*, 4 (5 (106)), 6–15. <https://doi.org/10.15587/1729-4061.2020.209847>
12. Shim, Y., Atkinson, M. P. (2018). Analysis of artillery shoot-and-scoot tactics. *Naval Research Logistics*, 65 (3), 242–274. <https://doi.org/10.1002/nav.21803>
13. Świętochowski, N. (2019). Rules of artillery employment in combat operations. *Scientific Journal of the Military University of Land Forces*, 192 (2), 280–293. <https://doi.org/10.5604/01.3001.0013.2599>
14. Krzyzanowski, S. (2018). How to assess the accuracy of artillery fire. *Scientific Journal of the Military University of Land Forces*, 187 (1), 25–39. <https://doi.org/10.5604/01.3001.0011.7355>
15. Amorim, C. B., Augusto, A. da S., Gonçalves, R. F. B. (2025). A Constant Trinitrotoluene Equivalence Fit for Blast Wave Position Versus Time Data. *Propellants, Explosives, Pyrotechnics*, 50 (7), 44–54. <https://doi.org/10.1002/prep.12071>
16. Hammond, T. R., Midtgaard, O., Connors, W. A. (2021). A Bayesian Network Approach to Evaluating the Effectiveness of Modern Mine Hunting. *Remote Sensing*, 13 (21), 4359. <https://doi.org/10.3390/rs13214359>

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