Proceedings of 5th International Conference CNDGS'2026
ISSN 2669-2023 (print) / ISSN 2538-8959 (on-line) / **https://doi.org/10.47459/cndcgs.2026.68**

Simulation-based Decision Support for Artillery Target Engagement

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Abstract

This paper presents a simulation-based decision support approach for artillery target engagement, focusing on the integration of stochastic modelling and reliability-based evaluation into fire planning. Traditional artillery methods rely on deterministic models and consumption norms, which provide limited insight into the variability of fire effectiveness. The proposed approach employs Monte Carlo simulation to model firing accuracy and munition effects, producing probabilistic distributions of target damage. These outputs are evaluated using reliability-based criteria, enabling comparison of firing methods in terms of effectiveness, probability of success, and ammunition consumption. Results demonstrate that optimized firing methods can achieve the required effect (≥30% target damage) with the desired reliability (84%) while significantly reducing ammunition expenditure and exposure time compared to traditional approaches. The study highlights the potential of simulation-based decision support to improve efficiency and decision-making in artillery fire planning.

KEY WORDS: *artillery fire control; decision support; Monte Carlo simulation; fire effectiveness; target engagement; reliability-based evaluation.*

Citation: Vajda M.; Varecha J.; Liška R.; Šalapa A.; Krompolc F. Simulation-based decision support for artillery target engagement. In Proceedings of the Challenges to National Defence in Contemporary Geopolitical Situation, Brno, Czech Republic, 7-10 September 2026. ISSN 2538-8959, **https://doi.org/10.47459/cndcgs.2026.68**

1. Introduction

Artillery remains one of the most decisive components of contemporary land warfare, as evidenced by recent high-intensity conflicts and supported by current research on artillery effectiveness and fire support systems [1]. At the same time, the operational environment has undergone significant transformation, characterized by increased battlefield transparency, rapid counter-battery response capabilities, and severe logistical constraints, particularly in terms of ammunition availability. These factors impose strict requirements on the efficiency of artillery fire, as ineffective fire not only wastes limited resources but also increases the exposure of firing units to enemy countermeasures. Contemporary artillery effectiveness is increasingly shaped by the integration of simulation environments, advanced training technologies, and automated data processing, which enhance both analytical capabilities and operational decision-making under uncertainty [2-6].

In current practice, artillery fire planning is largely based on deterministic analytical models and standardized firing procedures derived from established doctrines and consumption norms [7]. While these approaches provide robust and operationally simple solutions, they rely on simplified assumptions and offer only limited insight into the expected effectiveness of a selected firing method. However, artillery fire is inherently stochastic, as variability in firing accuracy, target location errors, and munition effects introduces significant uncertainty into the engagement process. Experimental and simulation-based studies confirm that inaccuracies in positioning, firing data, and environmental inputs significantly affect artillery effectiveness and reliability of outcomes [8-11]. Previous research has demonstrated that firing data accuracy and error propagation have a substantial impact on fire effectiveness [12], and neglecting this variability may therefore lead to suboptimal decisions, particularly under conditions of resource constraints and operational risk.

Recent advances in computational methods enable the application of stochastic modelling and simulation for evaluating weapon effectiveness. Monte Carlo simulation has been widely applied in weapon effectiveness modelling [1], [13], providing probabilistic outputs that better reflect real-world conditions compared to traditional analytical methods. At the same time, ongoing research highlights the importance of improving fire control procedures and decision-making processes [14-16]. Despite these advances, the practical use of simulation as a decision support tool remains limited, as most existing approaches focus primarily on modelling fidelity rather than on supporting operational decisions.

This paper addresses this gap by proposing a simulation-based decision support approach for artillery target engagement. The approach integrates stochastic modelling with reliability-based evaluation, enabling the comparison of alternative firing methods in terms of effectiveness, risk, and ammunition consumption. The objective is to provide a practical and operationally relevant tool for improving decision-making in artillery fire planning under conditions of uncertainty.

2. Theoretical background and decision support framework

The effectiveness of artillery fire is determined by the interaction of two key components: firing accuracy and munition effects. Both components are inherently stochastic and influenced by multiple sources of uncertainty, including target location errors, ballistic dispersion, meteorological conditions, and variability in munition performance. These factors have been extensively studied in both classical artillery theory and modern weapon effectiveness modelling approaches [1], [13,15,16]. Despite the probabilistic nature of these phenomena, their practical application in fire planning is often simplified, which limits the ability to fully account for uncertainty in operational decision-making.

2.1 Traditional approaches to fire effectiveness evaluation

Traditional artillery theory models firing accuracy using probabilistic error systems, typically decomposed into systematic and random components. These approaches are formalized in both national doctrines and NATO-aligned standards, where firing errors are represented using statistical descriptors such as probable errors or standard deviations [17]. However, in practical fire control procedures, these probabilistic models are frequently reduced to deterministic estimates based on expected values, tabulated firing data, and predefined ammunition consumption norms [7].

While such approaches provide robust and operationally simple solutions, they inherently neglect the variability of real-world engagements. As a result, fire planning is typically based on average values that do not reflect the full range of possible outcomes. Similarly, the effects of artillery munition are often evaluated using simplified damage models or empirical effectiveness tables, which do not fully capture the spatial variability of fragmentation effects or the probabilistic nature of target damage.

Previous studies have shown that even relatively small inaccuracies in firing data can significantly influence the resulting effectiveness of artillery fire [12]. Additional research on fire control procedures, including meteorological corrections and manual calculation methods, further highlights the sensitivity of artillery effectiveness to input uncertainties [18]. These findings indicate that deterministic approaches may lead to suboptimal decisions, particularly in conditions where resource constraints and operational risks are critical. Traditional and manual fire control methods, although operationally robust, are limited in their ability to address uncertainty, adapt to dynamic conditions, and exploit modern computational capabilities [19-22].

2.2 Stochastic modelling and Monte Carlo simulation

To overcome the limitations of deterministic approaches, modern research increasingly employs stochastic modelling techniques. Monte Carlo simulation has become a widely used method for modelling weapon effectiveness due to its ability to represent complex systems with inherent randomness [13,15,16]. In the context of artillery, Monte Carlo methods are used to simulate a large number of firing events, each representing a possible realization of the engagement under given conditions.

These simulations incorporate probabilistic firing errors, dispersion patterns, and variability in munition effects, enabling the generation of distributions of fire effectiveness rather than single deterministic values. Previous studies have demonstrated the applicability of such approaches using probabilistic damage models, including PK matrices and Carleton-type damage functions [13,15], which provide a more realistic representation of the interaction between shell impacts and target elements.

Recent work also emphasizes the importance of incorporating environmental and meteorological factors into effectiveness modelling, as these can significantly influence firing accuracy and overall outcomes [22]. In addition, simulation-based approaches have been applied to evaluate artillery system performance under different operational scenarios, demonstrating their potential for supporting analytical and experimental studies. However, these approaches are still predominantly used for modelling purposes and are not fully integrated into decision-making processes. Recent research extends simulation-based approaches beyond kinetic effects to include environmental impact, terrain mobility, and broader operational consequences of artillery fire [23-26].

2.3 Decision support in artillery systems

The increasing complexity of the operational environment has led to a growing emphasis on decision support systems in military applications. In artillery systems, decision support is closely linked to fire control processes, where commanders must rapidly evaluate multiple factors, including target characteristics, available resources, and operational constraints.

The evolution of decision support systems in artillery increasingly incorporates automation, data fusion, and advanced sensing, improving responsiveness, situational awareness, and operational effectiveness [27-30]. Other studies focus on improving specific aspects of fire control, such as firing data calculation, correction procedures, and adaptation to modern weapon systems [14,18]. While these contributions enhance the accuracy and efficiency of fire control processes, they generally rely on deterministic outputs or rule-based recommendations.

As a result, current approaches provide limited support for decision-making under uncertainty. In particular, they do not offer a systematic way to evaluate alternative firing methods based on both expected effectiveness and the probability of achieving required outcomes. These limitations highlight the need for a decision support approach that explicitly incorporates uncertainty and provides interpretable outputs for operational use. Such an approach is presented in the following section.

2.4 Simulation-based decision support framework

The proposed approach is designed as a decision support framework that enables the evaluation and comparison of alternative artillery firing methods under conditions of uncertainty. Rather than increasing modelling complexity, the objective is to transform simulation outputs into information that is directly applicable to operational decision-making.

The framework represents artillery fire effectiveness as a stochastic process composed of two interconnected components: the dispersion of shell impacts and the effects of munition on target elements. These components are modelled using probabilistic methods consistent with contemporary artillery theory and NATO-aligned error modelling approaches. Monte Carlo simulation is employed to generate a large number of realizations of artillery fire for a given firing configuration, where each realization represents one possible outcome of the engagement.

As a result, the framework produces distributions of fire effectiveness values instead of single deterministic estimates. From a decision-making perspective, three key evaluation parameters are considered: expected fire effectiveness, reliability of achieving the required effect, and ammunition consumption. A key feature of the framework is the introduction of reliability-based evaluation, where the effectiveness of a firing method is expressed as the probability of achieving a specified level of target damage.

This enables the formulation of decision criteria such as achieving a required level of damage (e.g., 30%) with a defined reliability (e.g., 80–90%). Such criteria allow commanders to compare alternative firing methods in terms of both effectiveness and risk, rather than relying solely on average values. By linking probabilistic simulation outputs with operational decision criteria, the proposed framework transforms modelling results into actionable decision support information.

From an operational perspective, this represents a shift from deterministic, rule-based fire planning toward adaptive and risk-informed decision-making. Commanders are no longer limited to predefined firing procedures but can select firing methods based on quantified trade-offs between effectiveness, reliability, and resource consumption. This approach supports more flexible, efficient, and context-aware decision-making in modern operational environments. Simulation and war-gaming approaches represent key tools for analysing complex operational scenarios and supporting decision-making in uncertain environments [2,5,31,32].

3. Results

3.1 Experimental scenario

The proposed decision support framework was verified using a simulation experiment representing a typical artillery engagement. The scenario involved a battery engaging an infantry area target composed of multiple elemental targets distributed within a defined area. The engagement was conducted under standard conditions using firing parameters representative of operational practice. Firing errors were modelled probabilistically in accordance with NATO-aligned error models, incorporating both systematic and random components.

The scenario parameters are summarized in Table 1. The required effect was defined as achieving at least 30% target damage corresponding to commonly accepted criteria for target destruction [7,17]. The required reliability level was set to 84%, which approximately corresponds to one standard deviation in a normal distribution of outcomes. This value represents a commonly used probabilistic threshold in engineering and operational analysis, where it reflects a balance between achieving a sufficiently high probability of success and avoiding excessive resource expenditure.

Table 1.

Parameters of the simulated engagement scenario

Parameter	*Value*
Target type	Infantry in attack formation
Target dimensions	200 × 100 m
Number of firing guns	8
Munition type	HE fragmentation
Required effect	≥ 30% target damage
Required reliability level	84%

3.2 Evaluated firing methods

Several firing methods were evaluated within the scenario, including a baseline method derived from standard fire control procedures and alternative configurations differing in the distribution of aiming points, number of rounds, and firing patterns. The baseline method reflects current doctrinal practice, where firing parameters are determined using predefined rules and consumption norms [7], while the alternative methods were designed to explore different trade-offs between concentration of fire, spatial coverage of the target, and ammunition expenditure.

More specifically, the evaluated firing methods differed in the spatial distribution of aiming points within the target area. The baseline method employed a linear distribution of aiming points corresponding to the eight firing guns, arranged in three depth lines within the target area. The spacing between adjacent aiming points within each line was 25 m, while the distance between depth lines was 33 m. This configuration reflects a conventional approach emphasizing uniform coverage of the target area.

Method A maintained the same general structure of three depth lines but modified the spacing parameters. The distance between aiming points was increased to 33 m, and the distance between depth lines was extended to 105 m. This resulted in a more dispersed fire pattern, increasing the coverage of the target area while reducing the overlap of effects.

Method B further reduced the number of depth lines to two, while maintaining a spacing of 33 m between aiming points and increasing the distance between depth lines to 120 m. This configuration represents a compromise between coverage and concentration of fire, with fewer aiming points distributed over a larger area.

Method C employed a fundamentally different approach, where the aiming points of the firing guns were distributed along a circular pattern with a radius of 90 m. This configuration emphasizes radial coverage of the target area and represents the most geometrically symmetric fire distribution.

Importantly, all evaluated methods were configured to achieve the same operational objective, allowing for a direct comparison of their effectiveness, reliability, and efficiency under identical conditions. The spatial distribution of aiming points relative to the target area is illustrated in Figure 1, providing a visual comparison of the evaluated firing configurations.

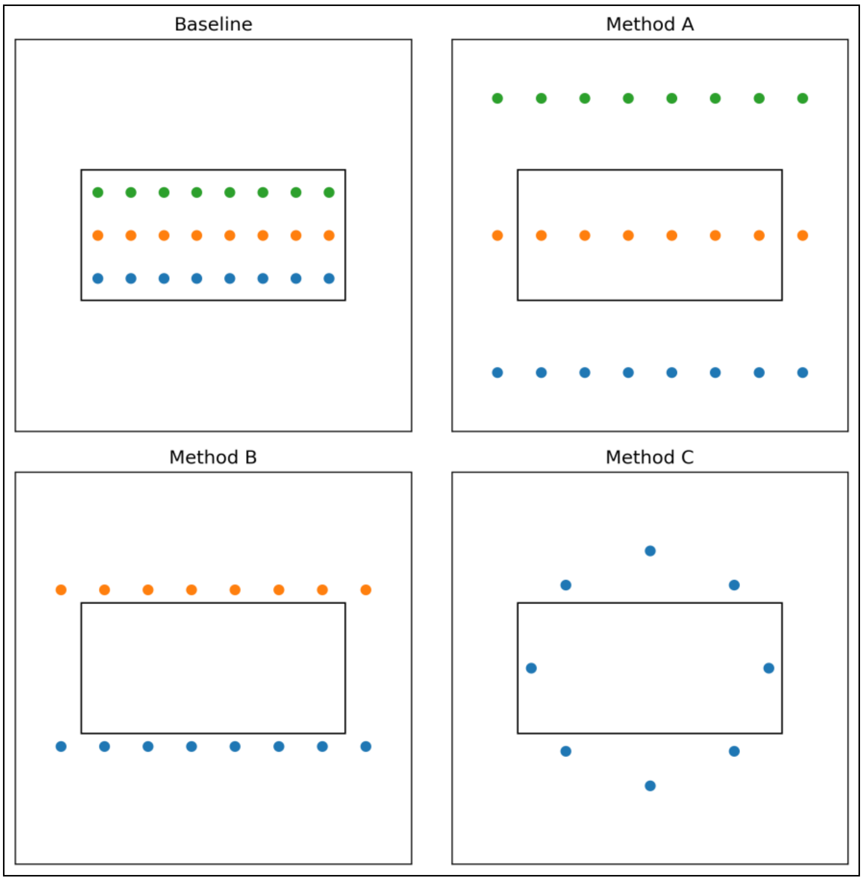

Fig. 1. Schematic representation of evaluated firing methods and their spatial relation to the target area (200 × 100 m).

This schematic representation facilitates the interpretation of the simulation results presented in the following sections.

3.3 Simulation Outputs

Monte Carlo simulation was used to generate a large number of realizations of artillery fire for each evaluated firing method. Each simulation run represented one possible outcome of the engagement, incorporating variability in firing accuracy, target location, and munition effects. As a result, fire effectiveness was expressed as a probabilistic distribution rather than a single deterministic value.

The primary output of the simulation was the proportion of affected elemental targets, expressed as target damage. Based on these results, several indicators were derived, including mean fire effectiveness, probability of achieving the required damage threshold (≥30%), empirical reliability levels, and ammunition consumption associated with achieving the desired effect.

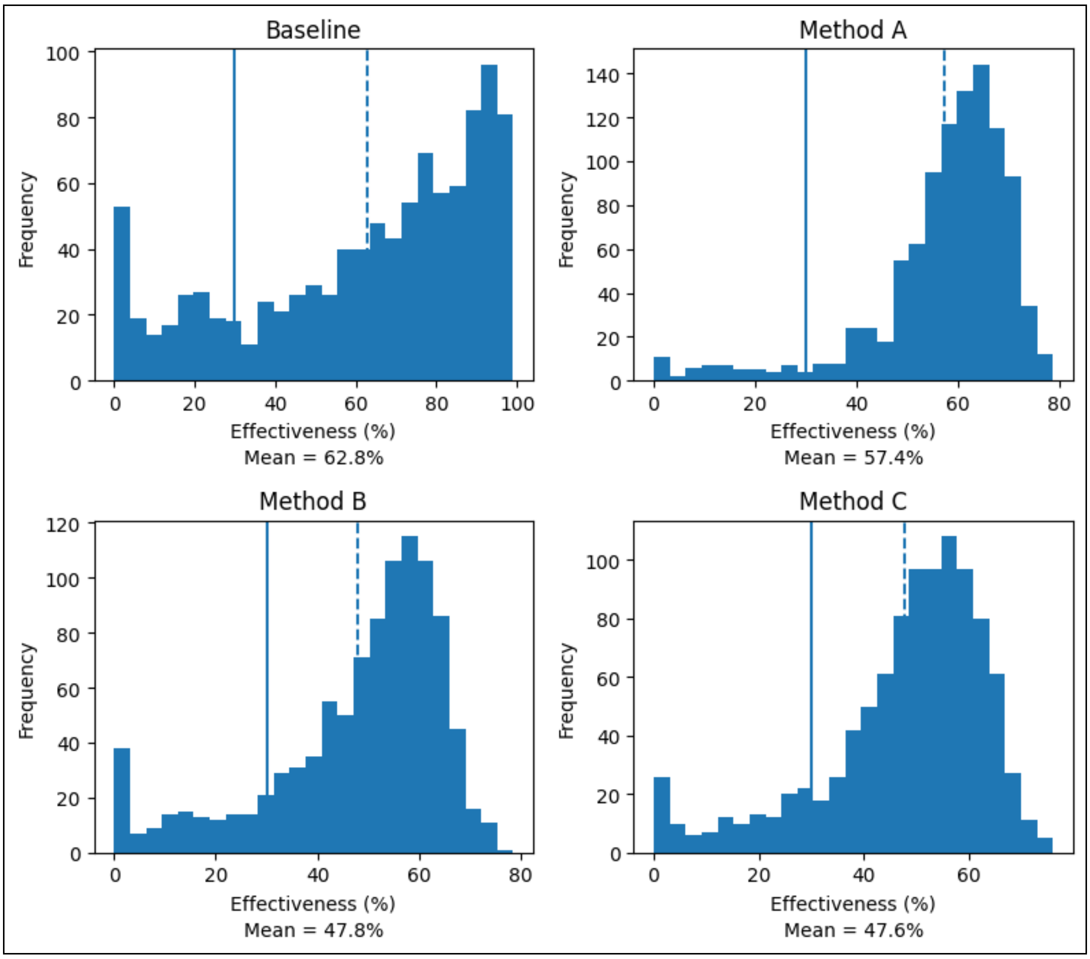

Fig. 2. Distribution of simulated fire effectiveness for evaluated firing methods.

Figure 2 illustrates the distribution of simulated fire effectiveness for the evaluated firing methods. The results clearly demonstrate that artillery fire outcomes cannot be represented by a single deterministic value, but rather form a distribution reflecting the stochastic nature of the engagement. The baseline method achieves the highest average effectiveness (approximately 63%), while alternative methods produce lower mean values in the range of approximately 48–57%.

However, the distributions also reveal substantial differences in variability. The baseline method exhibits a wider spread of outcomes, indicating less consistent performance and a higher degree of uncertainty. In contrast, alternative firing methods produce more concentrated distributions, suggesting more predictable and controlled effects.

The solid vertical line represents the threshold for target destruction (30%), illustrating that all methods are generally capable of achieving the required effect. Nevertheless, the variability of outcomes differs significantly between methods, which has direct implications for reliability and decision-making.

3.4 Comparison of firing methods

The comparison of firing methods reveals substantial differences not only in effectiveness, but also in reliability, resource consumption, and operational implications.

The results show that the baseline method does not satisfy the required reliability level, despite achieving higher average effectiveness. This demonstrates that reliance on mean effectiveness alone may lead to incorrect conclusions regarding the suitability of a firing method. In contrast, all alternative firing methods meet the required criteria, highlighting the benefit of evaluating fire effectiveness in probabilistic terms.

In addition to effectiveness and reliability, the evaluated methods differ significantly in terms of resource requirements. The baseline method requires a total of 72 rounds, corresponding to 9 rounds per gun distributed across three aiming points. Method A requires 48 rounds (6 rounds per gun across three aiming points), while Methods B and C require only 32 rounds (4 rounds per gun), with Method B employing two aiming points and Method C a single aiming point per gun.

These differences have a direct impact on operational exposure. The baseline method results in the longest duration of fire mission execution, increasing the vulnerability of artillery units to counter-battery fire. Method A reduces exposure time, while Methods B and C further minimize the duration of engagement, representing the most favorable solutions from a survivability perspective.

Figure 3 presents the probability of achieving a given level of target damage for the evaluated firing methods. The intersection of the destruction threshold (30%) and the required reliability level (84%) defines the operational decision criterion for selecting an appropriate firing method.

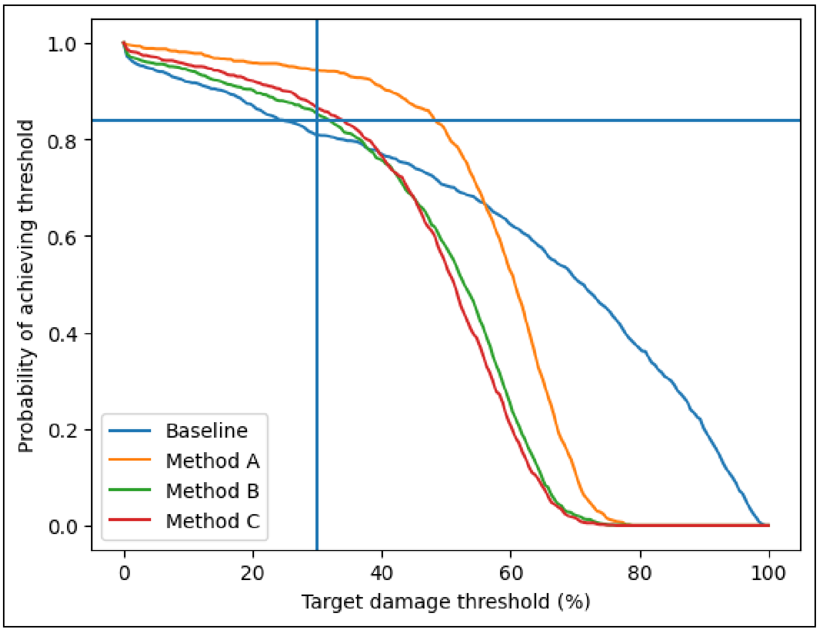

Fig. 3. Probability of achieving target damage as a function of effectiveness threshold for evaluated firing methods.

Overall, the results demonstrate that simulation-based decision support enables the identification of firing methods that not only meet effectiveness and reliability requirements, but also significantly reduce ammunition consumption and operational risk.

Furthermore, the analysis confirms that firing methods with similar mean effectiveness may exhibit substantially different reliability profiles. In some cases, methods with slightly lower average effectiveness provide a higher probability of achieving the required threshold, making them more suitable for operational use. These findings highlight the limitations of decision-making based solely on expected values and emphasize the importance of considering the full distribution of outcomes.

3.5 Key findings for decision support

From a decision support perspective, several key findings can be identified. First, artillery fire effectiveness must be understood as a probabilistic quantity rather than a deterministic value. The variability of outcomes plays a critical role in determining whether operational objectives will be achieved.

Second, reliability-based evaluation provides a practical and operationally meaningful criterion for comparing firing methods. By defining effectiveness requirements in terms of probability, commanders can make decisions that explicitly account for uncertainty and risk.

Third, the results demonstrate that traditional firing methods are not necessarily optimal in terms of resource efficiency or reliability. Simulation-based evaluation enables the identification of alternative firing configurations that achieve the required operational effect with significantly lower ammunition consumption.

Finally, there is a direct relationship between ammunition consumption and exposure time in the firing position. Methods requiring fewer rounds reduce the duration of fire missions and consequently decrease the vulnerability of artillery units to counter-battery fire. This demonstrates that probabilistic decision support contributes not only to improved effectiveness, but also to enhanced survivability.

4. Discussion

The results of this study confirm the fundamental limitations of deterministic approaches to artillery fire planning. Although such methods remain operationally practical and widely used, they do not adequately capture the variability inherent in artillery engagements. As demonstrated in previous research, inaccuracies in firing data, environmental conditions, and error propagation can significantly influence fire effectiveness and lead to deviations from expected outcomes [12]. Consequently, decision-making based solely on deterministic estimates may fail to ensure the required operational effect.

The application of stochastic modelling and Monte Carlo simulation addresses these limitations by explicitly representing uncertainty. This is consistent with prior studies that have demonstrated the suitability of probabilistic approaches for modelling weapon effectiveness and munition–target interaction [13,15,16]. Unlike traditional analytical methods, simulation-based approaches provide distributions of possible outcomes, enabling a more realistic representation of artillery fire.

However, while existing research has largely focused on improving modelling accuracy, the present study emphasizes the transformation of simulation outputs into actionable decision support. In this context, a key contribution of the proposed framework is the introduction of reliability-based evaluation as a central decision criterion. Traditional approaches typically rely on expected values or predefined consumption norms [7], which do not reflect the probability of achieving a required operational effect. By contrast, the proposed approach enables the evaluation of firing methods in terms of both effectiveness and the likelihood of achieving a specified damage threshold.

This perspective aligns with broader trends in military decision-making, where increasing operational complexity requires the integration of simulations into planning processes [31]. Research on fire control systems and command and control environments highlights the importance of combining data, models, and communication processes to support effective decision-making [18-21]. The proposed framework extends these efforts by providing a quantitative mechanism for comparing alternative firing methods under uncertainty.

A particularly important finding of this study is that the doctrinal baseline method does not guarantee the required reliability of achieving the desired effect, despite its higher average effectiveness. This challenges the assumption that traditional firing procedures inherently provide sufficient operational performance. Instead, the results indicate that methods with lower average effectiveness but higher consistency may be more suitable from an operational perspective.

Another significant implication of the results is the demonstrated potential for reducing ammunition consumption and exposure time without compromising effectiveness. Optimized firing methods were shown to achieve the required effect with substantially fewer rounds, which directly reduces the duration of fire missions and enhances the survivability of artillery units. This finding is particularly relevant in modern operational environments, where counter-battery threats impose strict constraints on the duration of fire missions and the efficient use of available resources.

At the same time, the practical implementation of the proposed framework requires further development. The current results are based on a simulation environment with predefined parameters and controlled conditions. For operational deployment, it will be necessary to integrate the framework with real-time data sources, automated fire control systems, and user-friendly decision support interfaces. Moreover, effective use of probabilistic outputs requires that decision-makers are able to interpret and apply reliability-based information, which highlights the need for intuitive visualization methods. From a broader perspective, artillery decision-making is increasingly linked to resource optimization and risk-based planning, where effectiveness must be balanced with limited resources and operational constraints [33-36].

Overall, the discussion confirms that simulation-based decision support has the potential to significantly enhance artillery fire planning. By shifting from deterministic to probabilistic evaluation, the proposed approach enables more informed, flexible, and efficient decision-making, while also improving resource efficiency and operational survivability.

5. Conclusions

This paper presented a simulation-based decision support approach for artillery target engagement, focusing on the integration of stochastic modelling and reliability-based evaluation into the fire planning process. The proposed framework addresses the limitations of traditional deterministic approaches, which, although operationally practical, provide only limited insight into the variability and uncertainty of artillery fire.

The results demonstrate that artillery fire effectiveness cannot be adequately represented by a single deterministic value. Instead, it must be understood as a probabilistic outcome influenced by multiple sources of uncertainty, including firing accuracy, target location errors, and variability in munition effects. By applying Monte Carlo simulation, the proposed approach enables the generation of distributions of possible outcomes, providing a more realistic basis for evaluating firing methods.

A key contribution of this study is the introduction of reliability as a central evaluation parameter. By expressing effectiveness in terms of the probability of achieving a required level of target damage, the framework allows for the formulation of operationally meaningful decision criteria. This enables commanders to select firing methods not only based on expected effectiveness, but also with respect to the likelihood of mission success.

The simulation experiment confirmed that alternative firing methods can achieve the required operational effect (≥30% target damage) with the desired reliability level (84%), while significantly reducing ammunition consumption compared to the baseline method. In the evaluated scenario, optimized methods reduced ammunition expenditure from 72 rounds to as few as 32 rounds, representing a substantial increase in efficiency. At the same time, reduced ammunition consumption directly translates into shorter duration of fire missions and decreased exposure of firing units to counter-battery fire, thereby improving operational survivability.

An important finding is that the doctrinal baseline method does not guarantee the required reliability of achieving the desired effect, despite achieving higher average effectiveness. This highlights the limitations of decision-making based solely on expected values and demonstrates the necessity of incorporating probabilistic evaluation into fire planning processes.

From a broader perspective, the proposed approach supports the transition from deterministic, rule-based fire planning toward adaptive and data-driven decision-making. By linking stochastic simulation outputs with operational decision criteria, the framework provides a practical foundation for the development of advanced decision support tools in artillery systems.

Future research will focus on several key areas, including the integration of the proposed framework into operational fire control systems, the incorporation of real-time data inputs, and the automation of optimization processes for selecting firing methods. In particular, further development will explore the application of machine learning and artificial intelligence techniques to support adaptive selection of firing configurations and to improve the efficiency of decision-making under dynamic operational conditions.

Additional work is also required to validate the proposed approach using experimental and real-world data, as well as to develop visualization techniques that facilitate the interpretation of probabilistic outputs in operational decision-making contexts.

Overall, the results demonstrate that simulation-based decision support provides a practical means of bridging the gap between modelling and operational decision-making. By enabling the evaluation of firing methods in terms of effectiveness, reliability, and resource consumption, the proposed approach supports more informed, adaptive, and risk-aware fire planning.

In conclusion, simulation-based decision support represents a viable and valuable approach for improving artillery fire planning in modern operational environments, enabling more effective, reliable, and resource-efficient decision-making while simultaneously enhancing the survivability of artillery units. Furthermore, the integration of advanced data-driven methods, including artificial intelligence, represents a promising direction for the development of next-generation artillery fire control systems.

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