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Firing Data Accuracy and its Impact on the Effectiveness of Artillery Fire

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Abstract

Artillery fire must be both timely and accurate to be effective. Predicted fire is a method that utilizes available data, such as meteorological, ballistic, and location information, to achieve first-round fire for effect. The level of accuracy required for such firing data may vary depending on the national regulations and tactical situation. In this study, the authors compared the effectiveness of predicted artillery fire using two different levels of firing data accuracy. The findings indicate that utilizing modern assets and instruments to achieve higher accuracy standards can significantly decrease the amount of ammunition required to achieve the same result on the target.

KEY WORDS: *artillery fire, accuracy, fire for effect, ammunition consumption, firing data, predicted fire*

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1. Introduction

Indirect fire support is a crucial element for ground forces in the successful execution of their military operations. The ongoing conflict between Russia and Ukraine serves as a reminder of its significance. According to available sources, approximately 20,000-50,000 pieces of artillery ammunition of various calibers are fired daily and both sides struggle to provide enough ammunition to troops [1]. When planning fire support, artillery commanders must consider principles of fire direction and control. The objective is to achieve the desired outcome with minimal rounds fired. This reduces the risk of detection by the enemy and also minimizes the logistical footprint [2, 3].

Artillery fire must be timely and accurate to be effective. However, its accuracy can be influenced by many factors, such as meteorological conditions, target location errors, and many others. As a result, artillery fire is not always delivered accurately on target. The distance between the mean point of impact of the artillery shells and the target is referred to as the delivery accuracy error. However, this error can be minimized by applying appropriate means and processes, resulting in increased efficiency of artillery fire on the target [4, 5].

The precise firing data needed for truly effective fire for effect (FFE) can be obtained mainly in two fundamentally different ways. The first approach is the adjust fire procedure, which is highly accurate but has the drawback of potentially exposing the location of our guns and allowing the enemy to respond. Alternatively, the second approach, known as predicted fire, entails obtaining precise firing data prior to firing a round. The more accurate the data, the more successful FFE will be, resulting in substantial savings on ammunition [6].

The article emphasizes the importance of acquiring precise firing data to increase the effectiveness of predicted fire. It argues that the implementation and utilization of modern and accurate means by all artillery units would significantly reduce ammunition usage while achieving the same effect on the target.

As a method of investigation, an analysis of currently applied accuracy standards for obtaining first-round FFE firing data was performed [3,7]. Results were compared with the level of accuracy of modern assets commonly used in advanced armies. Based on the accuracy of investigated instruments and methods, authors created increased accuracy standards. Comparative analysis of resulting firing data errors both for current and increased accuracy standards was conducted, using mathematical methods of artillery fire errors reduction and target segmental transformation [8]. The resulting data was used to calculate the optimal consumption of artillery shells needed to achieve the desired effect on three different types of targets.

The research was conducted on a model situation of the Armed forces of the Slovak Republic, where currently valid accuracy standards for first-round FFE were set in 2010 [3,7]. Computations of errors and shell consumption were conducted

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for the Howitzer D-30A and shell OF-462, currently used in eastern Ukraine but also by the Armed forces of the Slovak Republic. Determining the specific amount of ammunition savings for a different weapon system and different doctrinal accuracy standards would require further research.

2. Input Conditions

The accuracy standards of the input data used to prepare firing data indicate the probable errors in determining the individual values that are used in the mathematical model of artillery fire. These errors are essentially determined by the accuracy achieved by the devices or tools used to measure the values involved. In the analytical part of the research, the authors identified two levels of accuracy of source data allowing artillery units to apply the procedure of predicted fire:

- *Current accuracy* – level of relatively inaccurate data, but still allowing first-round FFE, according to current applicable regulations in the Armed forces of the Slovak Republic [3,7].
- *Increased accuracy* – level of accuracy achievable when utilizing modern devices, equipment, and procedures.

The authors meticulously analyzed the modern devices and equipment already in use in the Armed Forces of the Slovak Republic to determine the specific achievable values for the proposed level of increased accuracy. Several types of modern lightweight multifunctional devices, including those installed on vehicles and unmanned systems, are already being used to determine the location of targets within units with high accuracy [9, 10]. For the purposes of this article, the JIM COMPACT device will be considered in conjunction with the TNF STERNA device. According to the manufacturer's information, the probable error of determining the target's location is at the level of 8.2 meters and sometimes even less. Therefore, this value will be used as the level of increased accuracy in this article [11].

Artillery weapon systems can be equipped with navigation and positioning devices that use inertial and/or Global Navigation Satellite System (GNSS) technology. When using a GNSS positioning device, the accuracy of positioning is guaranteed under standard conditions at a level of up to 10 meters. However, in practice, the achieved accuracy is often even higher. For the article, a value of 9 meters will be considered as a level of increased accuracy. Inertial navigation and positioning devices of artillery weapon systems can achieve an accuracy of less than 1 milliradian when determining the azimuth or direction. In addition, current computer technology and access to digital map data, even in field conditions, significantly increase the accuracy when determining altitudes. Most modern armies use digital maps contained in several systems, which offer accurate digital maps for determining altitude with a standard accuracy of 1 meter. This means that the probable error of determining the altitude of the target and the firing position can be reduced to a value of 1 meter and achievable orientation accuracy is 1 mil [12-14].

Through the necessary digitalization of the battlefield, it is now possible to transmit the required data almost instantly. This includes weather information. By using modern meteorological stations to assess the atmosphere and ballistic wind, coupled with powerful computing technology and data linking of different levels of command using modern HARRIS-type connecting means, meteorological data can be provided to artillery fire units almost immediately after the end of the sounding. With automated and secure data transmission, it may soon be possible to provide fire units with meteorological reports immediately before the actual preparation of the fire task. However, this will only be possible in rare cases, as meteorological sounding cannot be carried out continuously due to the airspace above the battlefield being flooded with meteorological sounding balloons. Therefore, the average time of staleness of meteorological reports will be kept at the level of 2 hours when analysing both standard and increased accuracy of firing data during research [15].

Table 1.

Acceptable parameters of the input data used for predicted artillery fire

Input data errors		*Current accuracy*	*Increased accuracy*
Target location probable error magnitude	range	25 m	8,2 m
	deflection	25 m	8,2 m
Weapon location probable error magnitude	range	25 m	9 m
	deflection	25 m	9 m
Altitude probable error magnitude		5 m	1 m
Gun aiming in azimuth probable error magnitude		4 mil	1 mil
Staleness of meteorological data		2 hours	2 hours
Muzzle velocity probable error magnitude		0,4 %	0,1 %
Charge temperature probable error magnitude		1,5 °C	1,5 °C
Sight rectification probable error magnitude	vertical	1 mil	0,5 mil
	horizontal	0,6 mil	0,6 mil
Calculation of firing data probable error magnitude	range	5 m	0 m
	deflection	10 m	0 m

Muzzle velocity radars to accurately determine the initial velocity of projectiles are also available. These radars utilize the Doppler effect and the fast Fourier transformation algorithm to measure the real speed of the projectile, ensuring a much higher level of accuracy compared to the traditional methods of determining cartridge chamber wear, inserting depth gauge, or by shooting at field ballistic station. With modern muzzle velocity radars, an accuracy of better than 0.1% can be achieved, which will be considered as the increased accuracy value for the research. Temperature sensors with higher sensitivity are used to measure the temperature of charges, and their accuracy is better than that of older types of thermometers. Moreover, each gun can determine the temperature of the charge independently, eliminating the inaccuracy caused by the temperature difference of the charges in the entire artillery unit performing the fire mission [16]. The guaranteed accuracy of determining the temperature of the charge is nowadays at the level of 1.5 °C.

The calculation of firing data can be done either using an onboard control system or an external computer with appropriate software for preparing firing data. This means that errors in manual or graphic methods using maps, planchets or graphs, as well as calculation errors due to rounding of partial calculations, are either negligible or have no significant impact on the overall probable error. Therefore, calculation errors for the conditions of increased accuracy standards will not be considered within research (its size will be zero). Current accuracy standards were identified in applicable regulations, field manuals and technical manuals currently valid in the Armed forces of the Slovak Republic. Both current and increased accuracy standards can be found in Table 1.

3. Methodology of Work

It is not always possible to investigate the theory of artillery fire through real shooting. However, by using the theory of probabilities and mathematical statistics, we can study the movement of a projectile along a ballistic curve and its impact on the terrain. This helps us understand the position of a certain point around which all possible values of a random variable are grouped [17], [18]. We can also examine another value that shows how the individual values are scattered around the aiming point. The simplest example of artillery fire is the firing of one gun at a point (small-sized target). To achieve the objective of the article, it is important to take into account a more intricate system. This system would involve an artillery battery engaging larger targets with specific dimensions. This would resemble the reality of the battlefield more closely [19].

From this point of view, it is important to consider three levels of factors. The first level involves the potential errors in firing at a single target using one gun. The second level concerns the possible errors in firing by a battery of artillery pieces. To address this, we need to reduce the probable errors of each gun into a single reduced system of artillery fire errors for the whole unit. Finally, the third level involves firing at a larger target, which requires a segmental transformation of the reduced errors of the firing data.

3.1 Delivery Accuracy Errors of a Single Gun

The system of errors of artillery fire consists of a set of random variables that cause the impact of the bullets to deviate from the center of the target. These errors are unpredictable and can arise from various factors such as target location errors, gun location errors, errors in the detection of meteorological conditions, errors in ballistic and technical preparation, firing table errors, and errors in computations of firing data [20]. These errors follow a normal distribution pattern, which means that the overall random error in distance and direction is also subject to this law. Delivery accuracy errors can be expressed by formulas [4]:

$$Er_{DA} = \sqrt{Er_{TL}^2 + Er_{WL}^2 + Er_{MET}^2 + Er_B^2 + Er_T^2 + Er_{FT}^2 +} \sqrt{Er_{CAL}^2} \tag{1}$$

$$Ed_{DA} = \sqrt{Ed_{TL}^2 + Ed_{WL}^2 + Ed_{AZ}^2 + Ed_{MET}^2 + Ed_T^2 +} \sqrt{Ed_{FT}^2 + Ed_{CAL}^2} \tag{2}$$

where: Er_{DA}, Ed_{DA}– delivery accuracy probable error in range and deflection, Er_{TL}, Ed_{TL} – target location probable error in range and deflection, Er_{WL}, Ed_{WL} – weapon location probable error in range and deflaction, Ed_{AZ} – gun azimuth aiming error in deflection, Er_{MET}, Ed_{MET} – meteorological data probable error in range and deflection, Er_B – ballistic factors probable error in range, Er_T, Ed_T – technical factors probable error in range and deflection, Er_{FT}, Ed_{FT} – firing tables probable error in range and deflection, Er_{CAL}, Ed_{CAL} – calculation of firing data probable error in range and deflection.

Another group of errors that affect the deviation of the impact of individual rounds from the mean point of impact is the dispersion or round-to-round errors. Dispersion errors are random and non-recurring errors that occur with each subsequent shot. These errors manifest themselves differently each time. The causes of dispersion errors are small random deviations of the influences acting on the projectile when fired in the barrel and outside it, and during its flight along the ballistic path. In the past, it was confirmed by calculations and experiments that the dispersion of rounds follows the law of normal distribution. The firing tables of each artillery weapon system provide numerical values of the probable dispersion errors in range, direction, and height.

Knowing the delivery accuracy and round-to-round errors allows us to determine the total errors [4]:

$$Er_{TE} = \sqrt{Er_{DA}^2 + Er_{RR}^2} \tag{3}$$

$$Ed_{TE} = \sqrt{Ed_{DA}^2 + Ed_{RR}^2} \tag{4}$$

where: Er_{TE}, Ed_{TE}– total probable errors in range and deflection, Er_{DA}, Ed_{DA}– delivery accuracy probable error in range and deflection, Er_{RR}, Ed_{RR}– round-to-round probable error in range and deflection.

3.2 Reduction of Delivery Errors for an Artillery Unit

When carrying out artillery fire with multiple guns, the battery's system of errors needs to be taken into account. To simplify the calculations of this system, a method was developed to reduce the errors. This involves replacing the battery's fire error system with a fictitious gun's error system. By doing this, we can reduce the actual structure of the system of errors of artillery fire. Basic principle of the reduction of the system of firing errors is, that it is essentially a redistribution of partial components of the system of firing errors, but not a change in overall accuracy. Therefore, the basic requirement of the reduction can be expressed as the total probable error of the must be the same before and after the reduction. It means [4]:

$$Er_{TE} = \sqrt{Er_{RDA}^2 + Er_{RRR}^2} \tag{5}$$

$$Ed_{TE} = \sqrt{Ed_{RDA}^2 + Ed_{RRR}^2} \tag{6}$$

where: Er_{TE}, Ed_{TE}– total probable errors in range and deflection, Er_{RDA}, Ed_{RDA}– reduced delivery accuracy probable error in range and deflection, Er_{RRR}, Ed_{RRR}– reduced round-to-round probable error in range and deflection.

Reduced delivery accuracy probable errors can be calculated using relations [4]:

$$Er_{RDA} = \sqrt{Er_{DA}^2 \times rr_B} \tag{7}$$

$$Ed_{RDA} = \sqrt{Ed_{DA}^2 \times rd_B} \tag{8}$$

where: Er_{RDA}, Ed_{RDA}– reduced delivery accuracy probable error in range and deflection, Er_{DA}, Ed_{DA}– delivery accuracy probable error in range and deflection, rr_B, rd_B– reduction coefficients in range and deflection.

Reduction coefficients can be determined using the correlation coefficients of an individual gun and a battery. Correlation coefficients characterize the interdependence between individual gun shots and between the shots of individual pieces of the battery [4]:

$$rr_B = \sqrt{\frac{{cr_G}^2 + (k-1) \times {cr_B}^2}{k}} \tag{9}$$

$$rd_B = \sqrt{\frac{{cd_G}^2 + (k-1) \times {cd_B}^2}{k}} \tag{10}$$

where: rr_B, rd_B– reduction coefficients in range and deflection, k – number of guns in battery, cr_G, cd_G – correlation coefficients of gun in range and deflection, cr_B, cd_B – correlation coefficients of battery in range and deflection.

3.3 Segmental Transformation of Reduced Errors of Firing Data

The system of errors of artillery fire and its reduction deals with the case when shooting at a point target is considered. For the case of engaging targets with specified dimensions, artillery fire theory considers the so-called segmental transformation. It is a transformation of the dimension of the target to a size that ensures that the elemental target is located with equal probability in any location of the transformed target size. However, this transformation is only applicable to repeating phenomena, specifically delivery accuracy errors. Additionally, the target's dimensions are defined by its width and depth, with the width being perpendicular to the firing direction and the depth being in the direction of fire. This yields a rectangular shape, which can be segmented using the aforementioned process. Segmental transformation of reduced delivery accuracy probable errors are defined by the relations [4]:

$$Er'_{RDA} = \sqrt{{Er_{RDA}}^2 + 0{,}038 \times D^2} \tag{11}$$

$$Ed'_{RDA} = \sqrt{{Ed_{RDA}}^2 + 0{,}038 \times W^2} \tag{12}$$

where: Er'_{RDA}, Ed'_{RDA}– segmentally transformed reduced delivery accuracy probable error in range and deflection, Er_{RDA}, Ed_{RDA}– reduced delivery accuracy probable error in range and deflection, rr_B, rd_B– reduction coefficients in range and deflection, D- depth of the target, W- width of the target

3.4 Determining the Consumption of Ammunition to Achieve the Desired Effect

To achieve the expected firing effect of a target, there are fundamentally two methods that can be employed. The first method is based on continuously engaging and observing the target to judge when, or if, the desired effect occurred. The advantage of this method is that, usually no more ammunition is consumed than is necessary to achieve the desired effect. On the other hand, surprise caused by a massive fire may not be achieved at the beginning, which can significantly reduce its effectiveness. Similarly, it can be very difficult for an observer to estimate in real time the extent of damage caused by artillery fire and thus the achievement of the desired effect. Also, this method of determining the necessary consumption to achieve the expected effect of the artillery fire does not apply to fire support planning.

The second method is based on the prediction of the effectiveness of the specific artillery fire mission. It is applicable also for engaging unobserved targets and for ammunition consumption planning. Knowing artillery fire error budget, ammunition lethality parameters, and target dimensions it is possible to calculate predicted ammunition consumption for achieving the desired effect on the target. The method is based on the principle of the shelling parabolic density and is expressed by the following formula [8]:

$$N = q \times \frac{Er'_{RDA} \times Ed'_{RDA}}{AL \times \tau} \qquad (13)$$

where: N - number of rounds, q – efficiency coefficient, Er'_{RDA}, Ed'_{RDA} – segmentally transformed reduced delivery accuracy probable error in range and deflection, AL – ammunition lethal area, τ – rectification function.

4. Research Outcomes

The study of artillery fire cannot be conducted without a deep knowledge of its theory. In addition, the theory often cannot be verified in practice for logical reasons. The authors calculated the numerical characteristics of the error budget based on the determined conditions, using the theory of artillery firing and the chosen mathematical model of fire. These characteristics have been reduced for the entire firing artillery unit. The dimensions of the targets were transformed so that in the end it was possible to achieve the resulting values necessary for the calculation of the consumption of ammunition for different targets.

Table 2.
Numerical characteristics of errors of artillery fire for different accuracy of firing data elements

Analysed parametres	Unit	Accuracy standards					
Target number		1		2		3	
Accuracy standard level		Current accuracy	Increased accuracy	Current accuracy	Increased accuracy	Current accuracy	Increased accuracy
Delivery accuracy error in the range	Er_{DA} [m]	60,6327	38,7673	81,9551	63,0788	110,8428	93,0420
Delivery accuracy error in the deflection	Ed_{DA} [m]	45,1562	17,1410	59,4522	28,6889	78,5840	44,8840
Correlation coefficient of the gun in the range	cr_G	0,9494	0,8846	0,9950	0,9873	0,9969	0,9944
Correlation coefficient of the battery in the range	cr_B	0,7375	0,8296	0,6173	0,9060	0,6447	0,9495
Correlation coefficient of the gun in the deflection	cd_G	0,9940	0,9600	0,9986	0,9938	0,9987	0,9961
Correlation coefficient of the battery in the deflection	cd_B	0,9877	0,9176	0,9884	0,9504	0,9873	0,9612
Reduced delivery accuracy probable error in the range	Er_{RDA} [m]	54,4143	37,6883	54,4844	39,8599	73,7668	63,7939
Reduced delivery accuracy probable error in the deflection	Ed_{RDA} [m]	45,0289	16,8036	59,1835	28,1290	78,1854	44,1835
Reduction coefficient of the battery in the range	rr_B	0,7646	0,8361	0,6712	0,9156	0,6939	0,9547
Reduction coefficient of the battery in the deflection	rd_B	0,9884	0,9226	0,9896	0,9554	0,9886	0,9652
Segmentally transformed reduced delivery accuracy probable error in the range	Er'_{RDA}	61,7731	47,7012	61,8349	49,4349	79,3508	70,1759
Segmentally transformed reduced delivery accuracy probable error in the deflection	Ed'_{RDA}	53,6899	33,7248	70,8709	48,0753	87,3668	58,9252
Rounds consumption to achieve effect	N [pcs]	238	115	78	43	672	401
Difference in consumption (pcs)		123		35		271	
% difference in consumption		51%		46%		40%	

The above-mentioned work methodology was applied to model situations of predicted fire of an artillery battery armed with 122 mm H D-30 howitzers, OF-462 projectile and fuze KZ-88. The whole battery occupies one firing position and consists of 8 howitzers. The currently valid minimum accuracy standard of the elements of firing data was applied, but also the increased accuracy proposed by the authors, both enabling first-round FFE. In the model examples, the battery engaged the following targets:

- *target number 1 – personnel in defensive positions*, dug in, target dimensions 150 x 150 m, desired effect *neutralization*, range of fire 6 km, charge 2,

- *target number 2 – personnel in an offensive position*, dimensions 200 x 150 m, desired effect *destruction*, range of fire 10 km, charge Zm (reduced),
- *target number 3 – self-propelled light artillery battery*, dimensions 200 x 150 m, desired effect *destruction*, range of fire 14 km, charge P (full).

The results of the analysis of the system of artillery fire errors and ammunition consumption for individual model examples, i.e. targets, are presented in Table 2. For clarity, the results in Table 2 are also color-coded.

A chart was created to illustrate the achieved results, as shown in Figure 1. It is evident that by adjusting the minimal accuracy standards for the preparation of firing data, there was a significant reduction in the total ammunition required to achieve the desired effect in all model examples.

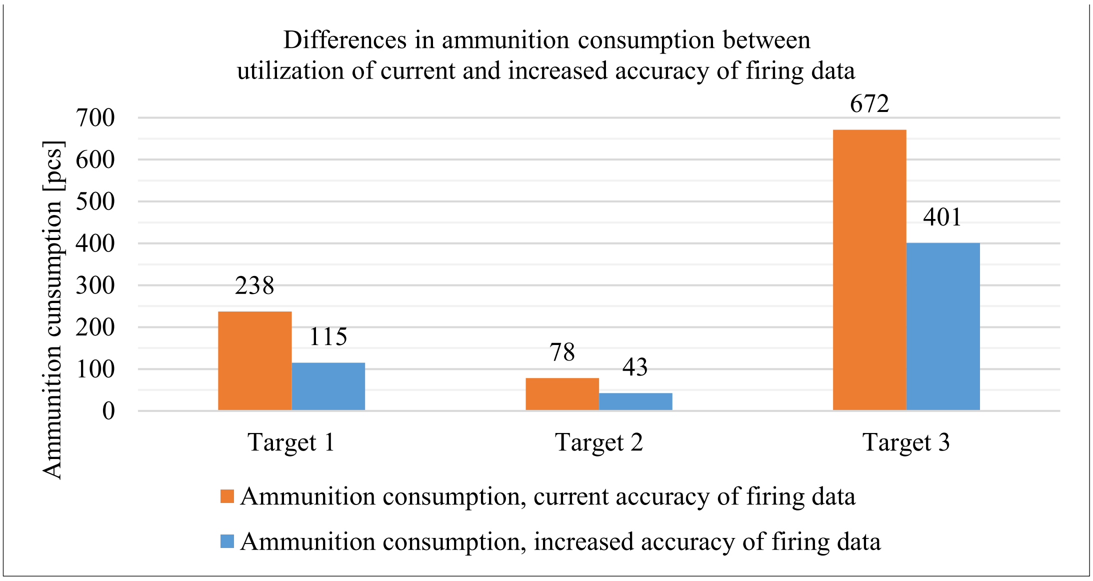

Fig. 1 Differences in ammunition consumption between utilization of current and increased accuracy standards for obtaining first-round FFE firing data.

For the individual targets, this resulted in a 51%, 46%, and 40% decrease in the total consumption of ammunition. Therefore, it can be concluded that by enhancing the accuracy of input data used for calculation of firing data, it is possible to significantly improve the efficiency of artillery fire. The situation in Ukraine highlights the need to consider the economy of fire support. Ukraine, like most NATO coalition states, does not have sufficient economic capacity to meet the requirements for fire support with a surplus [21, 22].

5.Conclusions

Through the analysis of the artillery fire on model examples, it was demonstrated that by improving the conditions under which the firing data are prepared, it is possible to achieve the same effect with a significant reduction in the ammunition used. This creates a clear objective for artillery commanders: to utilize the most precise methods and take advantage of the potential of modern devices and means to the fullest extent [23].

In theory, the number of firing guns is not the most important factor in achieving the desired effect. Rather, it is the amount of accurately delivered ammunition that matters. However, artillery experts might not agree with this statement. From a practical and tactical perspective, it is also crucial to consider how quickly the required number of shots can be delivered to the target area.

Enhancing the accuracy of artillery fire can lead to improved efficiency and reduced ammunition consumption. This phenomenon translates into a higher likelihood that the desired effect is achieved with fewer shots and a shorter amount of time spent in the firing position. In the contemporary era of advanced intelligence, surveillance, and target acquisition capabilities, the significance of these benefits cannot be overstated, as they can significantly increase the survival rate of an artillery unit on the battlefield. By reducing ammunition consumption and enhancing efficiency, the cost and logistic footprint of firing will decrease. In today's era of ammunition scarcity, every round saved can be crucial.

The article suggests guidelines for preparing firing data, taking into account the current technological equipment and its capabilities. This involves analyzing the error systems of each artillery weapon system and determining lethal areas for all available ammunition types. Using this information, recommended standards for ammunition consumption for different targets can be established. These standards will be useful for artillery commanders and fire support planners to plan fire support for maneuver units effectively, efficiently, and economically.

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