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Explaining the Ammunition Shortage: The Show vs. Have Military Power Game

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Abstract

The return of high-intensity conflict at Europe's borders has exposed the massive under-investment in ammunition by many Western states, relative to the normal availability of main weapons. This paper complements existing explanations for this relative imbalance with insights from a signaling game. In an environment where neither military budgets nor investment in ammunition can be observed, low-budget states may imitate the procurement strategy of high-budget states, and invest substantial amounts in visible weapon systems, to project an image of power. In this context, high-budget states have an incentive to over-invest in main weapons and neglect ammunition as a strategy to dissuade imitation by low-budget states. While this behavior may be rational in times of peace when perceptions may matter as much as capabilities, during wartime, the deficit in ammunition is extremely harmful, as it increases the likelihood of the opponent's victory.

Keywords - High-intensity warfare, Signaling game, Military power, Perceived power.

JEL Classification - D82; F52; H56; H57.

1 Introduction

Since the fall of the Iron Curtain, Western policymakers, particularly the European ones, have lived under the illusion of the ‘peace dividend.’ As the Soviet Union disappeared and the Russian economy went through a deep crisis, with its armed forces weakened during the transition to a market-based economy, Western policymakers championed a reduction in defense spending and redeployed the spared resources toward civil use and social programs. According to this rationale, shared by many laypeople, after the end of the communist-capitalist confrontation, Western countries would face no major threats in the future. In particular, autocratic regimes were expected to play the market game, get wealthier and better educated, and finally embrace democratic values (Fukuyama, 1992).

Moscow’s full-scale invasion of Ukraine in February 2022 ended this illusion. The aggression against a pro-European country at the EU’s border revealed that land-based, high-intensity warfare is not a thing of the past. Having overlook early warnings about a more belligerent Russia (the war in Georgia in 2008, the invasion of Crimea in 2014), the war in Ukraine shook the established military doctrines of EU member countries, which overnight had to confront their salient lack of preparedness for this type of conflict, a conclusion that underlies the emergency military guidelines wrote out in the Strategic Compass of March 2022 (Hartley, 2023).¹ Across the Atlantic, US military forces are not exempt of criticism. In July 2024, an influential bi-partisan commission appointed by the US Congress to review the US National Defense Strategy of 2022 underlined the significant unpreparedness of the US military forces to fulfill its missions (USCNSD, 2024).

The 3-year continuing war in Ukraine revealed some basic lessons from the past, which had been somehow forgotten. Besides high-tech sophisticated and quite expensive weapon systems, a high-intensity land-based war requires massive artillery, huge stocks of ammunition, basic equipment, lots of spare parts, workshops to repair damaged materials, and substantial logistics, in a war universe closer to World War II than Star Wars. A quick comparison of military capabilities of NATO and Russia as of 2024 shows that while NATO has a striking advantage over Russia in terms of active soldiers, aircrafts, naval forces and armored vehicles, the situation is balanced in terms of main battle tanks and artillery.²

To date, the most striking evidence of the West’s unpreparedness for a high-intensity, land-based war lies in the domain of ammunition. This topic is highly sensitive, as it raises questions about NATO military forces’ ability to fulfill their missions. Consequently, there is no official empirical assessment of the issue. However, if one carefully compiles the press reports based on official sources, the picture becomes neat. The journal *Le Monde*, on February 18, 2023, cited a French Parliament report, according to which the French Army’s ammunition stock would not last for more than a few weeks in a high-intensity conflict.³ War simulations performed in 2022 showed that, in a high-intensity conflict, the United Kingdom would exhaust its ammunition stocks in just eight days (HouseofCommons, 2024), while the Bundeswehr’s stocks would last somewhere between a few hours and a few days (Aries et al., 2023). In the early months of the war, Ukraine received approximately 350 units of 155-mm Howitzers from the US and allies, pushing their total stock to 1,600 artillery pieces; a substantial number of older generation howitzers were prepared for decommissioning and could have been sent too.⁴ However, given the shortage of ammunition, the Ukrainian army could shoot some 2,000 rounds per day in the early months of 2024, compared to 10,000 rounds a day shot by the Russian forces.⁵

In an interview for the *Financial Times* on July 1st, 2024 - Rob Johnson, former director of the office of net assessment and challenge with the UK Ministry of Defence acknowledged that “In any larger-scale operation, we would run out of ammunition rapidly... Our defences are too thin, and we are not prepared to fight and win an armed conflict of any scale”. Retired Air Marshal Edward Stinger, told the *Financial Times* that Britain had a “Shopfront military, one that can excel on

¹In an official document, the European Commission acknowledged that between 2006 and 2020, EU member countries recorded a deficit of 1,100 billion euros in military spending, estimated against the NATO spending norm of 2% of GDP (EuropeanCommission, 2024).

²Data provided by *Statista*, extracted on 28 December 2024, reveal 850,000 armored vehicles for NATO vs. 161,000 for Russia, 11,390 main battle tanks vs. 14,780 main battle tanks, 5,900 tower artillery pieces vs. 8,350, respectively.

³See “L’armée française manque de munitions pour la haute intensité”, *Le Monde*, February 18, 2023.

⁴See Mark Cancian and James Anderson, “Expanding equipment options for Ukraine: The case of artillery”, CSIS, January 23, 2023, www.csis.org/analysis/expanding-equipment-options-ukraine-case-artillery.

⁵See Jack Watling, “The peril of Ukraine’s ammo shortage”, *Time*, February 19, 2024, time.com/6694885/ukraine-russia-ammunition/.

display and exercises.... but when you go beyond the facade, there's precious little on the shelves and no production lines behind it".⁶

In recognition of the ammunition crisis against the background of the emergency of the war in Ukraine, in July 2023 the EU set up the Act in Support of Ammunition Production (ASAP) to bolster the production capabilities of the EU defence industry, with special focus on ammunition production (Fabbrini, 2024). The EU set a target of 1 million shells to be delivered to Ukraine in the first semester of 2024, which could hardly be achieved by the end of the year (Borel, 2024).

Despite their substantial military strength, the United States of America are not exempt of similar criticism. In a report on January 2023, Marc Cancian, a senior advisor at the Center for Strategic and International Studies called attention on the shortage of 155-mm artillery rounds to which the US army was exposed after delivering substantial quantities to Ukraine.⁷ In an interview for the journal National Security on July 18, 2023, the same expert argues that NATO forces could run out some varieties of ammunition if there is a war with China or some other major power. Actually, in 2023 the US had to buy ammunition from South Korea, as its production line could not follow the consumption of shells in Ukraine. Beaver and Fein (2024) note that poor ammunition planning by the US Department of Defense has been a consistent characteristic of the post-1989 period. They underline that "The Pentagon was caught off guard by the amount of artillery shells needed by the Ukrainian and Israeli military after being attacked, and supply is short." They call attention on the fact that, by mid-2024, the US air force including 111 bombers could launch no more than 4.95 joint air-to-surface standoff missiles per bomber, and the Navy's 23 active destroyers, cruisers, and submarines could fire zero Tomahawks and at most 1.76 standard missile each. Finally, in July 2024, the above-mentioned Report of the Commission to review the US National Defense Strategy bluntly states "Previous NDS Commissions have warned that Department of Defense has systematically under-invested in munitions, choosing to raid these accounts as quick fixes to solve budget shortfalls" (USCNDS, 2024). The report further emphasizes that "The Ukraine war and the Israel-Hamas war, however, vividly demonstrate that modern wars are likely to be protracted and consume a lot of munitions, from the relatively basic 155-mm artillery rounds, to Army Tactical Missile System (ATACMS) missiles, to air defense interceptors, and the *United States simply does not have enough of such munitions on hand*".

In general, the peace dividend rationale and the resulting budget cuts provide the main explanation for the poor readiness for large conflicts of the Western states. Other explanations are specific to the EU: they include policy and defense industrial base fragmentation (European Commission, 2024; Fabbrini, 2024; Mueller, 2024), excessive rivalry between EU states focused on narrow national interests, strong competition between EU defense firms (Hartley, 2023), reluctance by private and public funding organisations to support the defense sector⁸, conflicts between various EU institutions (Csernaton, 2021) and the limited coordination role of the European Commission (Besch, 2019).

However, these useful explanations cannot account for the notorious shortage of ammunition *relative* to the normal stock of major weapons. Following the pioneering analysis by Veblen (1899), a substantial body of literature in social sciences has been dedicated to the analysis of conspicuous or positional goods. Veblen indicated that the consumption of luxury goods can be motivated by humans' desire to signal their wealth and thus obtain a higher status. Psychologists have been interested in identifying the emotional drivers of this behavior, such as pride, self-image, social image, desire for uniqueness, and so on (see Kumar et al. (2022) for a meta-analysis). These psychological motives might have also contributed to the over-investment in visible weapon systems, which can be viewed as positional goods in a state's arsenal. An alternative explanation would bring into the picture planners' overconfidence in the ability of the defence industrial base to rapidly ramp-up production of ammunition, combined with some optimism about would-be ammunition pooling and sharing among NATO member countries in case of conflict.⁹ The war in Ukraine revealed how difficult this task can be, and how large the required investment is.¹⁰

In this paper, we provide a signaling explanation to the relative shortage of ammunition, spare parts and other invisible inputs, and the mirror over-investment in visible major weapons, that complements the existing explanations. Our analysis emphasizes the weapon procurement strategy as a means of conveying information about the true military power of a state, in a context where

⁶See "UK military unprepared for conflict of any scale, warns ex-defence official", *Financial Times*, July 1st, 2024.

⁷See "Rebuilding US inventories: Six critical systems", Center for Strategic and International Studies, January 9, 2023; www.csis.org/analysis/rebuilding-us-inventories-six-critical-systems

⁸The European Investment Bank has denied support to defense projects until May 2024.

⁹We thank one of the referees for pointing out this alternative explanation.

¹⁰See Josh Luckenbaugh and Stew Magnuson, "Arms manufacturers catching up with world's insatiable need for 155mm rounds", November 9th, 2024, *National Defense Magazine*.

external observers have only incomplete information about this strategic dimension. Limited information is an essential feature of international defense policy, where states try to emphasize their strengths and hide their weaknesses.

National defense, like any form of defense, is dissuasive if the opponent believes that you are stronger than him or her. In times of peace, the *swaggering goal* of military force receives substantial weight. As defined by Art (1980), swaggering is expressed in general by “displaying one’s military might at military exercises and national demonstrations and buying or building the era’s most prestigious weapons”. While the major weapons can be displayed in any demonstration of power, the stock of ammunition (and spare parts) is private information. Imagine now that the budget dedicated to conventional weapon procurement is private information, and that states have either high or low budgets. In this case, a low-budget state might buy and show as many main weapons as a high-budget state, to the expense of the stock of ammunition, just to manipulate the beliefs of the external observers and make them believe that it has a large budget, which in turn would prompt them to avoid conflict.

In our framework, this imitation strategy cannot be an equilibrium, since high-budget states might increase the procurement of main weapons up to the point where the imitation strategy no longer pays for a low-budget state. This mechanism is present in the analysis by Spence (2002), where high-skilled workers would push their education years to the limit where low-skilled workers, with a higher cost per education year, obtain no benefit from imitating them.¹¹

The game features a non-trivial separating equilibrium in which high-budget states under-invest in ammunition, spare parts, and other low-tech resources, to the benefit of visible, fancy high-tech weapons systems. The results of our analysis show that over-investment in visible systems essentially depends on the budget gap between states and a ‘show-off’ parameter that adjusts the weight of perceived military strength against actual military strength in the state’s objective function. It is highly probable that in times of peace, states have a stronger preference for conveying an image of military strength, even if they must sacrifice some essential inputs for their actual defense. However, in times of conflict, the costs of showing off in good times appear to be a serious burden.

One cannot overstate Thomas Schelling’s contribution to the analysis of conflict and deterrence. His masterpiece, *The Strategy of Conflict* (Schelling, 1960), not only addressed major topics in the analysis of conflict with utmost analytical clarity but also guided game theory research toward answering fundamental questions such as those related to nuclear deterrence (Myerson, 2009). The question of how parties to a conflict can credibly signal their future conduct was present in his analyses. However, it was not until the publication of Michel Spence’s seminal paper (Spence, 1973) that signaling games received a rigorous analytical foundation, leading to countless applications.

In a traditional signaling game, information about the productive characteristics of the agents is private; high-type agents strive to reveal their type to the receiver by sending an appropriate signal, knowing that the low-type agents can imitate their actions. In general, the solution is a Bayesian Nash equilibrium, where senders’ actions and the receiver’s beliefs are mutually consistent (see the surveys by Riley (2001) and Sobel (2020)).

The signaling approach was used in the study of military strategy and international conflict for topics as various as famous successful military strategies in ancient China (Cotton and Liu, 2011), to commitment for fighting in conflict (Fearon, 1997; Spaniel, 2021), persuasion and disinformation strategies (Arce, 2024), forcing entry in the nuclear club (Jelnov et al., 2018), contemporary terrorist threats (Lapan and Sandler, 1993; Arce and Sandler, 2007; Zhuang et al., 2010).

The supply of defense services and the functioning of defense industries are naturally prone to informational asymmetries on both sides of the market. Governments may hide military spending or the size of future orders, while defense firms might not disclose true production costs, the expected duration of developing a new weapon, or its effectiveness. In a world with heterogeneous agents, those who bear the highest informational costs associated with unobserved characteristics may aim to send signals to reveal their type. This fully justifies the use of signaling models to address important topics in defense economics. Many general analyses, as applied to any buyer-supplier interaction, have direct implication for defense procurement. In the study by Chen and Zhang (2020), a privately informed seller would try to signal their type through persuasion and pricing strategy, and for Figueroa and Guadalupi (2023), an informed supplier uses both the selection of the test and information disclosure as a signaling device. There is a substantial literature on signaling, persuasion and deception in dynamic auctions, which provide for an essential

¹¹See also Vickers (1986) and Gal-Or (1989) for a similar reasoning as applied to monetary policy credibility and warranty coverage. Clingingsmith and Sheremeta (2018) built a lab experiment and find out that the results are consistent with a signaling equilibrium.

mechanism in weapon procurement (see for examples Avery (1998); Ausubel and Cramton (2006); Chang et al. (2015); Cisternas and Figueroa (2015)).

To the best of our knowledge, the set of studies directly applying Spence’s signaling game to economic problems pertaining to the defense sector is narrower. Lipow and Feinerman (2001) explained the relative under-investment in the quality of Israeli troops compared to the relatively high quality of their weapons. In their model, the quality of commanding officers cannot be observed directly. A good officer can make a more efficient use of the resources under his or her control, which can be shared between improving the qualification of the troops, or buying equipment. Investment in troops is an unobserved variable. Without a signaling strategy, low-skilled officers would invest in weapons as much as the more efficient high-skilled officers. The latter can signal their type by over-investing in weapon quality, which prompts lesser-quality officers to choose their optimal bundle of troop training and weapon acquisition. In contrast to their model, which considers only the pure strategies, our equilibrium selection method build on the analysis of a mixed-strategy equilibrium. Besancenot and Vranceanu (2006) studied a signaling game between commercial banks, who lack of expertise with European defence firms, and those firms that must finance new projects, by applying either for public funds or private funds. Their analysis revealed an inefficient allocation of funds determined by the poor quality of information, and urged EU policymakers to address this issue by rising the transparency of the defense projects. In contrast with the present study, in that analysis firms cannot provide a costly signal to reveal their type.

The paper is organized as follows. The next section introduces the main assumptions of the model. In Section 3, we analyze optimal choices under perfect information. The asymmetric information case is analyzed in Section 4, which also introduces the signaling equilibrium. Section 5 is our conclusion.

2 The model

2.1 Technology

Many weapon systems are made up of relatively expensive devices capable of launching lethal projectiles toward enemy targets and various incoming threats. In this category of weapons, we find traditional guns and their ammunition (bullets), howitzers and their artillery rounds, and more modern launchers and their rockets or missiles, such as those fired by the man-portable, fire-and-forget Stinger and Javelin, or the more sophisticated HIMARS and ATACMS, which have proven their large effectiveness in Ukraine (Petraeus and Roberts, 2024). In these examples, launchers and ammunition complement each other in the projection of force. A similar complementarity logic applies to any type of weapon, since ultimately, all weapons require a significant amount of ammunition to be effective, whether it be a howitzer, a lethal drone, or the most advanced attack helicopter.

Similar to the weapon and ammunition complementarity, one can consider the weapon and spare parts association; in a land-based, high-intensity war, weapons often break in contact with the enemy. Their proper functioning requires a substantial maintenance effort and large inventories of spare parts.

This logic of complementarity extends to many other aspects of the production of military power, which require relatively fixed proportions of inputs to achieve the greatest impact. Communications, troops, logistics, satellite surveillance, weapons of various kinds, and their ammunition must work together. At a more aggregate level, substitutions can be made to some extent, but no one can imagine a modern high-intensity war being won solely by naval forces or troops alone.

Thus, input complementarity is the key property of any meaningful military production function. In this paper, we assume that the functioning of a weapon system in the battlefield involves *perfect complementarity* between launchers and ammunition. Furthermore, to use an intuitive notation, we will refer to launchers as *howitzers*, in quantity C and to ammunition as *shells*, in quantity S . We assume that in a standard land-based conflict a howitzer can shoot α shells before it breaks down. Thus, any efficient allocation (or kit) of howitzers and shells should verify:

$$S = \alpha C. \tag{1}$$

We represents these efficient bundles as the bold line in Figure 1, to which we refer as the technology efficient line. For any given amount of howitzers C , disposing of more or less than αC shells is tantamount to a waste of resources. Investing more in shells is technically useless, since the excess shells cannot be used; investing less, means that some howitzers cannot be used. Therefore

kits located above (below) the efficient line correspond to a situation where shells (respectively howitzers) are the limiting factor in the production of defense service.

In line with the standard analysis of production functions with perfect complementary inputs, the *conventional military power* of a state is defined as:

$$D = \min\{C, S/\alpha\} \quad (2)$$

For kits (C, S) that are not on the technology efficient line, the military power is determined by the binding factor. If, for example, ammunition is the limiting input ($S \leq \alpha C$), then the military power D is simply:¹²

$$D = \varphi S. \quad (3)$$

where $\varphi = 1/\alpha$ is the slope of the technology efficient line.

While perfect complementarity is the natural assumption in this context, the model could be generalized for a ‘neoclassical’ military power function (Hartley, 2012), which allows for some limited substitutability between ‘visible’ and ‘invisible’ inputs, and would entail convex isoquants. The structure of our game with incomplete information would not change as long as the expansion path for the optimum has a positive slope; it would nonetheless become impossible to obtain an explicit solution.

2.2 Main goal of the state

In line with the four-goal analysis by Art (1980), we assume that states care about their actual military power as dedicated to the goals of defense, deterrence and compellence, and also obtain a benefit if they manage to persuade external observers that they dispose of a substantial military power. Actual and perceived power are related, but, as our analysis will point out, are not necessarily identical in an asymmetric information setting.

This dual goal can be captured in a simple way by a linear objective function of the state i :

$$V_i = (1 - \gamma)D_i + \gamma E[D_i|I], \text{ with } \gamma \in (0, 1) \text{ and } i = \{L, H\}. \quad (4)$$

where V_i is the government’s defence-related utility, D_i stands for actual military power as defined in Equation (2), and $E[D_i|I]$ is the perceived military power by external observers, contingent on their information set $\{I\}$, which includes all the relevant observed variables. The ‘show-off’ parameter γ captures policymakers’ preferences as it tunes the weight of the two partial goals in the general goal.

In times of peace, the relative importance of image can be quite large, while it should be low in conflict times, when the show-off rationale is replaced by a must-win rationale.

2.3 The budget constraint

For any state i , the conventional weapon budget can be used to buy howitzers (C_i) and shells (S_i). Let us denote by B_i the military budget of the state, and let p^C be the price of howitzers and p^S the price of shells. The budget constraint of a state i can be written as:

$$p^C C_i + p^S S_i \leq B_i \text{ with } i = (H, L). \quad (5)$$

If we assume that the cost and price of a shell, which requires relatively basic technology to be produced, does not vary from one country to another, we can use it as numeraire and set $p^S = 1$.¹³ We denote the relative price of howitzers to shells by $\eta = p^C/p^S > 1$. Then the budget constraint of the state can be written as:

$$\eta C_i + S_i \leq B_i. \quad (6)$$

However, given the former objective function in which both actual and displayed military power require the full use of inputs, it is certain that the budget constraint is saturated. We therefore can write the budget constraint simply as:

$$B_i = \eta C_i + S_i. \quad (7)$$

We denote by \bar{C}_i the maximal amount of howitzers a state can buy (the entire budget is used to buy howitzers), so $\bar{C}_i = B_i/\eta$.

¹²This expression is valid for the efficient kit too.

¹³This is obviously a simplification. The NATO standard 155-mm artillery rounds vary with respect to their explosive power and distance range; by mid-2024 their market price vary between 4,000 and 10,000 USD a piece.

2.4 Sources of heterogeneity

States differ with respect to many elements of their military power. In this analysis, on a Occam razor principle logic, we will consider that countries are almost identical, with heterogeneity measured along only one dimension of military power: the size of the budget dedicated to procurement of conventional weapons per million inhabitant.¹⁴ Governments use to disclose the total defense related expenses, and research institutions such as the Stockholm International Peace Research Institute (SIPRI), compile international comparisons of military expenses, including wages and pensions of the military, expenses on nuclear defence, logistics and maintenance, R&D, and expenses for conventional weapons. However, many governments would conceal the amount of expenses dedicated to the procurement of conventional weapons, which is considered as strategic information. This intrinsic opacity creates a typical asymmetric information environment.¹⁵

For our analysis, we assume that a fraction λ of the states (*type* – H states, or simply H states) have a high budget B_H , and a fraction $(1 - \lambda)$ of the states (*type* – L states or L states) have a low budget B_L , with $B_H > B_L$.

To bolster the readability of the model, we summarize in Table 1 the main variables introduced so far and their definitions.

Number of howitzers	C
Number of shells	S
The efficient ratio of shells by howitzer	α
Auxiliary variable, the slope of the efficient line ($\varphi = 1/\alpha$)	φ
The relative price of howitzers to shells	η
Defense capability level	D
National defense budget	B
The share of high-budget states	λ
Utility of the government	V
The weight of perceived capability	γ
Share of L-states imitating H-states	μ

Table 1: Definition of key variables

A key element of our analysis is the information structure of the problem. In the context of military power and military expenses, assuming perfect information is not realistic. However, it is useful to address this situation as a baseline against which we can later analyze the more plausible case of asymmetric information.

3 The perfect information case

Under perfect information, external observers have perfect foresight on the defense budget of any state, and of the investments in both howitzers and ammunition. Thus their expectations about the military capability of any state i matches the actual capability of that state, $E[D_i|I] = D_i$. By consequence, a state i that seeks to maximize V_i will choose the efficient kit (C, S) ($S = \alpha C$) that satisfies the budget constraint:

$$B_i = \eta C_i + \alpha C_i = (\eta + \alpha) C_i. \quad (8)$$

The optimal amount of howitzers and shells is:

$$C_i^* = \frac{1}{\eta + \alpha} B_i \quad (9)$$

$$S_i^* = \frac{\alpha}{\eta + \alpha} B_i. \quad (10)$$

where (*) indicates the perfect information optimal choice.

For any two states, one of the type H and the other of the type L ($B_H > B_L$), it turns out that $C_H^* > C_L^*$ and $S_H^* > S_L^*$.

According to the production function (Equation 3), the military power writes as:

¹⁴Alternatively, instead of considering the budget per person, the analysis would compare only countries of a similar size.

¹⁵Adding additional heterogeneity, such as a different relative price η , would not change in a significant way the structure of the problem.

$$D_i^* = \varphi S_i^* = \varphi(B_i - \eta C_i^*) \quad (11)$$

or, as a closed-form expression:

$$D_i^* = \frac{1}{\eta + \alpha} B_i. \quad (12)$$

We represent in Figure 1 the technology efficient line and the budget lines for a state H and for a state L . The slope of the technology efficient line is $1/\alpha = \varphi$ and the slope of the budget line is $-1/\eta$. Also, the optimal kits are represented as points M and N .

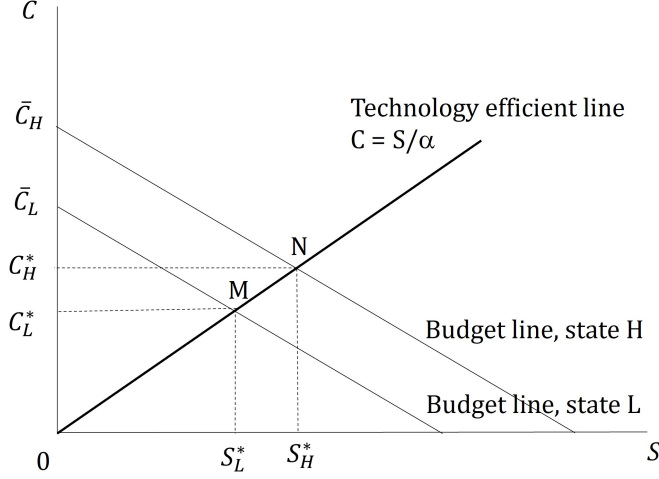


Figure 1: Optimal choices under perfect information.

4 The incomplete information case

In an incomplete information setting, external observers, including the military intelligence of rival states, do not know the military budget of other states; however, they know the distribution of states by budget (λ , or the frequency of H states in the total population of states), and might use observed signals to infer the type of the state.

With respect to the inputs of the production function, we assume that only the amount of main weapons (howitzers, launchers, etc.) can be observed through the orders placed by the Ministry of Defense to main contractors, satellite images that allow them to be counted in the field, and other intelligence gathering methods. On the other hand, the amount of ‘low-tech’ inputs (shells, spare parts, ammunition of various kinds) cannot be observed by external observers.

4.1 No trivial separating equilibrium

By ‘trivial’ separating equilibrium we understand a situation in which each type of state buys, in the incomplete information setting, its perfect information optimal kit, (C_H^*, S_H^*) and (C_L^*, S_L^*) respectively. If such an equilibrium exists, observers’ equilibrium beliefs must be correct:

$$\Pr[\text{type } L | C = C_L^*] = 1 \quad (13)$$

$$\Pr[\text{type } H | C = C_H^*] = 1 \quad (14)$$

Proposition 1 *Under incomplete information, if γ is large enough ($\gamma > \frac{\eta}{\eta + \alpha}$), the efficient choices under perfect information, (C_H^*, S_H^*) for state H and (C_L^*, S_L^*) for state L , cannot be an equilibrium of this game. On the other hand, if $\gamma < \frac{\eta}{\eta + \alpha}$ then separation prevails, and the two bundles can be an equilibrium.*

Proof 1 *A deceptive state L aiming to manipulate observers’ beliefs, would acquire as many howitzers as a state H , that is $C_L = C_H^* > C_L^*$ and consequently would undercut the procurement of shells to $S_L = B_L - \eta C_H^*$, which then becomes the binding input. By so doing, it makes observers*

believe it is of the strong type H , at the expense of a lower military power. The latter falls to $\tilde{D}_L(C_H^*)$ as defined by:

$$\tilde{D}_L(C_H^*) = \varphi(B_L - \eta C_H^*) < D_L^* \quad (15)$$

(The tilde indicates suboptimal choice.)

Thus, it is interesting for a L state to adopt the imitation (deception) strategy if:

$$(1 - \gamma)\tilde{D}_L(C_H^*) + \gamma E[D|C_H^*] > (1 - \gamma)D_L^* + \gamma E[D|C_L^*] \quad (16)$$

This is equivalent to:

$$\begin{aligned} (1 - \gamma)\varphi(B_L - \eta C_H^*) + \gamma\varphi(B_H - \eta C_H^*) &> \varphi(B_L - \eta C_L^*) \\ \gamma[(B_H - \eta C_H^*) - (B_L - \eta C_H^*)] &> \eta(C_H^* - C_L^*) \\ \gamma &> \frac{\eta}{\eta + \alpha} \end{aligned} \quad (17)$$

If $\gamma < \frac{\eta}{\eta + \alpha}$, a ‘trivial’ separating equilibrium exists. In this situation, the state has set the effective development of military power as its priority goal, and pays only limited interest to the image of strength it projects to outsiders. If $\gamma > \frac{\eta}{\eta + \alpha}$, there is an incentive for L states to copy the howitzer procurement strategy of the H states, thus the ‘trivial’ separating equilibrium in which both states acquire the perfect information, optimal kit of howitzers and shells, does not exist.

In the following we focus on the most interesting situation where states assign substantial weight to the image they convey to outside world, this is $\gamma > \frac{\eta}{\eta + \alpha}$. In this case, at least some L states if not all of them, have an incentive to deviate and imitate the howitzer procurement strategy of the H states, to make observers believe that they are of the strong type.

4.2 A naive hybrid equilibrium

We thus study a hybrid equilibrium in which some L states choose to imitate the H states and buy as many howitzers as the latter ($C_L = C_H^*$).

Let us denote by μ the fraction of L states that adopt the imitation strategy.

In this subsection, we assume that the H state cannot adjust the amount of howitzers it buys (it is subject to procurement stickiness), which explains why we refer to this equilibrium as ‘naive’. In the next sub-section, the analysis is generalized by allowing H states (and not only L states) to ‘strategically’ adjust the amount of howitzers bought.

Recall that if a H state buys the perfect information amount C_H^* , the number of shells $S_H^* = B_H - \eta C_H^*$ is efficient and the associated military power is:

$$D_H^* = \varphi(B_H - \eta C_H^*). \quad (18)$$

A deceptive state L which buys $\tilde{C}_L = C_H^*$ will undercut the procurement of shells which now becomes the binding input, with $\tilde{S}_L = B_L - \eta C_H^*$. It thus obtains a lower military power compared to the perfect information case:

$$\tilde{D}_L(C_H^*) = \varphi(B_L - \eta C_H^*). \quad (19)$$

We represent this situation in Figure 2. Because the kit $(\tilde{C}_L, \tilde{S}_L)$ is located above the efficient line, it corresponds to situations where shells are the limiting input in the production function with perfect complementarity. The suboptimal defense level of the L state is simply $\tilde{D}_L = \varphi\tilde{S}_L$, and the defense level of the H state is the optimal one under perfect information $D_H^* = \varphi S_H^*$.

For an external observer, the howitzer procurement strategy of a state can be written as:

$$\begin{cases} \sigma(H) = (C_H^*, S_H^*) \\ \sigma(L) = \begin{cases} (\tilde{C}_L = C_H^*, \tilde{S}_L = B_L - \eta C_H^*) & \text{with probability } \mu \\ (C_L^*, S_L^*) & \text{with probability } (1 - \mu) \end{cases} \end{cases}$$

We use Bayes’ rule to determine the equilibrium beliefs:

$$\begin{aligned} \Pr[\sigma(H)|C_H^*] &= \frac{\Pr[C_H^*|\sigma(H)] \Pr(\sigma(H))}{\Pr[C_H^*|\sigma(H)] \Pr(\sigma(H)) + \Pr[C_H^*|\sigma(L)] \Pr(\sigma(L))} = \frac{\lambda}{\lambda + \mu(1 - \lambda)} \\ \Pr[\sigma(H)|C_L^*] &= 0 \end{aligned}$$

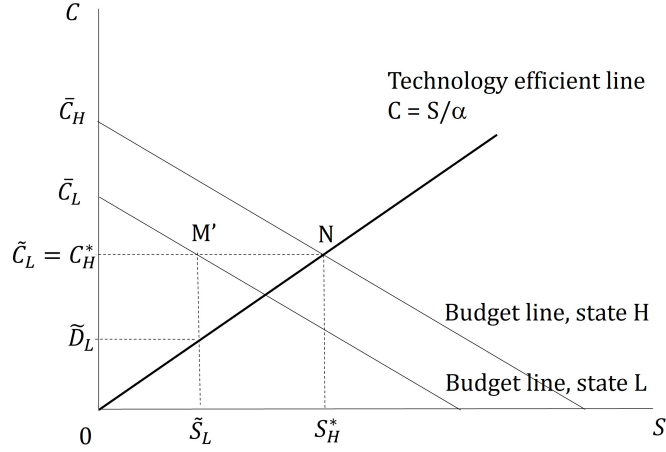


Figure 2: The ‘naive’ hybrid equilibrium.

leading to the expected military power conditional upon the number of howitzers $E[D|C_i]$:

$$E[D|C_L^*] = D_L^* = \varphi(B_L - \eta C_L^*) \quad (20)$$

$$\begin{aligned} E[D|C_H^*] &= \frac{\lambda}{\lambda + \mu(1 - \lambda)} D_H^* + \frac{\mu(1 - \lambda)}{\lambda + \mu(1 - \lambda)} \tilde{D}_L(C_H^*) \\ &= \frac{\lambda}{\lambda + \mu(1 - \lambda)} \varphi(B_H - \eta C_H^*) + \frac{\mu(1 - \lambda)}{\lambda + \mu(1 - \lambda)} \varphi(B_L - \eta C_H^*) \\ &= \varphi \left[(B_H - \eta C_H^*) - \frac{\mu(1 - \lambda)}{\lambda + \mu(1 - \lambda)} (B_H - B_L) \right] \end{aligned} \quad (21)$$

We recall that λ is the frequency of H states; the higher λ and the lower μ , the higher $E[D|C_H^*]$ is.

In this naive hybrid equilibrium, L states should be indifferent between copying the strategy of the H state, or following their perfect information investment in howitzers (that signals their type). This indifference condition allows us to determine the equilibrium frequency of deceptive L states, μ .

$$\begin{aligned} V_L(C_L^*) &= V_L(C_H^*) \\ (1 - \gamma)D_L^* + \gamma E[D|C_L^*] &= (1 - \gamma)\tilde{D}_L(C_H^*) + \gamma E[D|C_H^*] \\ (B_L - \eta C_L^*) &= (1 - \gamma)(B_L - \eta C_H^*) + \gamma \left[(B_H - \eta C_H^*) - \frac{\mu(1 - \lambda)}{\lambda + \mu(1 - \lambda)} (B_H - B_L) \right] \\ \mu &= \frac{\lambda}{(1 - \lambda)} \left[\frac{\gamma(B_H - B_L)}{\eta(C_H^* - C_L^*)} - 1 \right] \end{aligned} \quad (22)$$

or simply:

$$\mu = \frac{\lambda}{1 - \lambda} \left[\gamma \frac{\alpha + \eta}{\eta} - 1 \right] \quad (23)$$

A hybrid equilibrium is possible for $\mu \in (0, 1)$. It can be easily shown that condition (17) ensures that $\mu > 0$. At least some states L will always imitate the H states (if the latter implement the procurement strategy C_H^*). The condition $\mu < 1$ involves that $\gamma < \frac{1}{\lambda} \frac{\eta}{\eta + \alpha}$. From these two inequalities we infer that a hybrid equilibrium exists for:

$$\frac{\eta}{\eta + \alpha} < \gamma < \frac{1}{\lambda} \frac{\eta}{\eta + \alpha}. \quad (24)$$

As shown in Proposition 1, for $\gamma < \frac{1}{\lambda} \frac{\eta}{\eta + \alpha}$ the trivial separating equilibrium prevails. For $\gamma > \frac{1}{\lambda} \frac{\eta}{\eta + \alpha}$ the equilibrium is of the pooling type ($\mu = 1$), all L states copy the howitzer procurement strategy of the H states.

However, the pooling equilibrium cannot exist if the frequency of H states is relatively small. Indeed, if $\lambda < \frac{\eta}{\eta + \alpha}$ then $\frac{1}{\lambda} \frac{\eta}{\eta + \alpha} > 1$. Since $\gamma < 1$, it turns out that $\gamma < \frac{1}{\lambda} \frac{\eta}{\eta + \alpha}$.

4.3 The arms race and the signaling equilibrium

In a pooling or hybrid equilibrium, H states are penalized, as external observers cannot precisely infer their military strength from observation of their howitzer procurement strategy. For $\mu \in (0, 1)$ and $\lambda \in (0, 1)$, the expected military power as defined in Equation (21) is lower than the perfect information level: $E[D|C_H^*] < D_H^*$.

If a state deviates and buys (slightly) more howitzers than all the others, external observers should interpret this move as a signal for a H -type state.¹⁶ In this context, a state H has an incentive to buy slightly more howitzers than the others, because an incremental increase in the amount of howitzers has a negligible impact on the actual military power of this state, while bringing about a quantum jump in the *perceived* military strength of this state (from $E[D|C_H^*]$ to D_H^*).

However, as long as the military budget of the L states is not exhausted, any incremental increase in the procurement of howitzers can be copied by L states, leading to a new hybrid equilibrium. This dynamics is tantamount to a race to the top for the procurement of visible weapons.

When H states increase the level of investment in howitzers to C_H^s (with $C_H^s > C_H^*$) for signaling purpose, and a fraction μ of the L states imitate them, Equation (22) simply becomes:

$$\mu(C_H^s) = \frac{\lambda}{(1-\lambda)} \left[\frac{\gamma(B_H - B_L)}{\eta(C_H^s - C_L^*)} - 1 \right]. \quad (25)$$

Obviously, the equilibrium frequency of imitators among the L states declines with C_H^s :

$$\frac{\partial \mu(C_H^s)}{\partial C_H^s} < 0. \quad (26)$$

The over-investment in howitzers by a state H contributes to reducing both its military power and that of its potential imitator. By increasing C_H , the high-budget state increases the cost of imitation and reduces the gain in reputation for the low-budget state. Imitation ceases to be effective when C_H is high enough for the cost of replicating the signal (displaying the same high amount of howitzers) to exceed the gain in reputation for the imitator. Formally, imitation cancels-out as a meaningful strategy of the low-budget state for a critical \hat{C}_H , defined by $\mu(\hat{C}_H) = 0$ or:

$$\hat{C}_H = C_L^* + \frac{\gamma}{\eta} (B_H - B_L). \quad (27)$$

By adopting this high level of investment in howitzers, the state H unambiguously signals its type, since potential imitators have no further incentive to copy it. L states implement their perfect information optimal choice (S_L^*, C_L^*) . The resulting signaling equilibrium ensures separation of types.

Proposition 2 *In the signaling equilibrium, the over-investment in howitzers by the H -state is increasing in the ‘show-off’ parameter γ , in the budget gap $(B_H - B_L)$ and the technology coefficient α ; it decreases in the relative price of howitzers over shells, η .*

Proof 2 *The over-investment in howitzers by the H -state is:*

$$\begin{aligned} \hat{C}_H - C_H^* &= C_L^* - C_H^* + \frac{\gamma}{\eta} (B_H - B_L) \\ &= \frac{1}{\eta + \alpha} (B_L - B_H) + \frac{\gamma}{\eta} (B_H - B_L) \\ &= (B_H - B_L) \left[\frac{\gamma}{\eta} - \frac{1}{\eta + \alpha} \right]. \end{aligned} \quad (28)$$

Signs of the partial derivatives of the over-investment term with respect to parameters are obvious. The sign of the partial derivative with respect η is the sign of the term $[\eta - (\eta + \alpha)\sqrt{\gamma}]$, which is negative for $\gamma > \frac{\eta}{\eta + \alpha}$ (which is the existence condition of the hybrid equilibrium).

¹⁶Indeed, the opposite beliefs cannot be an equilibrium of this game: a L state has no incentive to raise its investment in howitzers and sacrifice its military power just to signal itself since $D_L^* < E[D|C_L^*]$.

The imitation-proof military power of the H state is:

$$\tilde{D}_H(\hat{C}_H) = \varphi(B_H - \eta\hat{C}_H) \quad (29)$$

$$= \varphi[(1 - \gamma)B_H + \gamma B_L - \eta C_L^*]. \quad (30)$$

The military power of the L states D_L^* has been previously defined by Equation (11) as:

$$D_L^* = \varphi(B_L - \eta C_L^*). \quad (31)$$

Despite the expensive signaling strategy, the H state enjoys a higher military power than the L state.

$$\tilde{D}_H(\hat{C}_H) > D_L^* \quad (32)$$

Figure 3 represents this signaling equilibrium. As previously shown, H states over-invest in howitzers and under-invest in shells as compared to the perfect information optimum; the decision is represented as the point N'' . As the kit (\hat{C}_H, \hat{S}_H) is located above the efficient line, shells are now the limiting input for the military capability of the state H . The suboptimal defense level of the H state is simply $\hat{D}_H = \varphi\hat{S}_H$. On the other hand, L states implement their perfect information choice (point M).

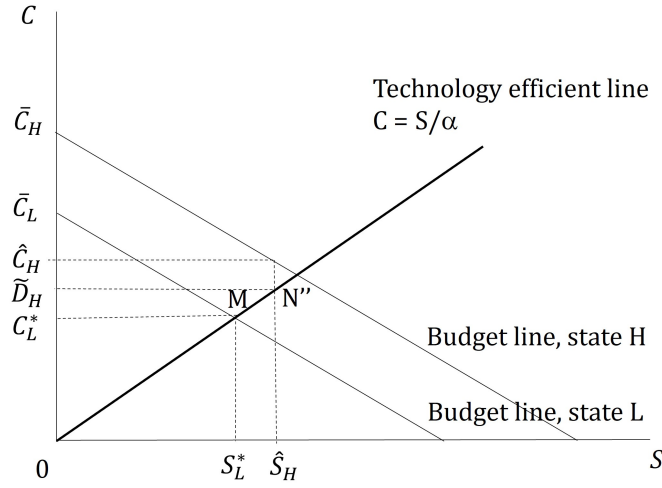


Figure 3: Signaling equilibrium.

Our proof of existence of the signaling equilibrium makes the implicit assumption that L states do have the resources to imitate the procurement strategy of H states, this is they can buy any amount of howitzers $C_L < \hat{C}_H$. This requires:

$$\eta\hat{C}_H < B_L \Leftrightarrow \frac{(B_H - B_L)}{B_L} < \frac{1}{\gamma} \left(\frac{\alpha}{\eta + \alpha} \right) \quad (33)$$

Obviously, all other things being equal, condition (33) is fulfilled if the budget gap $(B_H - B_L)$ is relatively narrow.

4.4 Signaling equilibrium and the budget limit

In the case of a large budget gap, $\frac{(B_H - B_L)}{B_L} > \frac{1}{\gamma} \left(\frac{\alpha}{\eta + \alpha} \right)$, separation occurs in a straightforward way when the H state buys $\bar{C}_H = B_L/\eta$. At this level, a L state would have used the entirety of its budget to buy howitzers, which makes any imitation impossible. In this equilibrium the military power of the H -state is:

$$\tilde{D}_H(\bar{C}_H) = \varphi(B_H - B_L). \quad (34)$$

The L -state implements its perfect information strategy and reveals its type.

We can check that the defense level of the H state is larger than the defense level of the L state:

$$\tilde{D}_H(\tilde{C}_H) > D_L^* = \varphi(B_L - \eta C_L^*) \quad (35)$$

which is true since the separation under resources limit required that $\frac{(B_H - B_L)}{B_L} > \frac{1}{\gamma} \frac{\alpha}{\eta + \alpha}$.

As an upshot of these, we can conclude that separation of types occurs for $C_H = \min \{ \hat{C}_H; \tilde{C}_H \}$.

5 Conclusion

The war in Ukraine, which has been unfolding since February 2022, was a tremendous shock to Western policymakers and citizens, as their hopes for a peace dividend fell to pieces overnight. The war now exposes major flaws in the defense doctrines of many EU countries, which had dismissed the possibility of ever engaging in a land-based, high-intensity war.

The lack of readiness for such a conflict is most evident in the realm of ammunition, spare parts, and other vital but less visible inputs. EU member states had ammunition stocks sufficient to resist a massive aggression for only a few days at most. Even the US, despite its tremendous military power, faced a shortage of artillery rounds and, at one point in 2024, had to resort to external procurement. Dramatically, until the first part of 2024, Ukrainian military forces had to cope with a massive shortage of artillery rounds, resulting in significant military casualties and making any offensive initiative almost impossible. In contrast, while there may be a shortage of advanced air defense systems, there is no critical shortage of main weapons such as main battle tanks, armored vehicles, and howitzers, which were provided to Ukraine on time (Borel, 2024).

There are several explanations for the relative shortage of ammunition, including psychological factors such as military planners' overconfidence in their capacity to rapidly ramp up production or their commitment to advanced weapons as symbols of national pride. The explanation provided in this paper complements these existing theories by emphasizing the signaling mechanism. In our analysis, external observers have only imperfect information about the military budgets of various states. In normal (peace) times, low-budget states might imitate the procurement strategy of high-budget states, and invest as much as the later in visible high-end weapon systems. The final goal of this persuasion being to dissuade potential aggressors from engaging in conflict. In this context, high-budget states might invest even more in visible equipment, only to signal their military strength. This repose lead to emergence of a signaling equilibrium, where low-budget states follow their perfect information strategy, and high-budget states under-invest in the dull yet essential inputs, such as artillery rounds. Our analysis shows how this cost of signaling in terms of reduced military power is related to a key parameter that captures the state's preferences for pretending versus actually having military strength.

Unfortunately, as the war in Ukraine reminds us, while posturing may be a meaningful goal in peacetime, it can have dramatic consequences in times of conflict, when deterrence by persuasion ceases to matter, and only defeating the aggressor matters. On a more positive note, EU member states have drawn important lessons from this war and are implementing significant adjustments to their defense strategies at both national and EU levels, fostering integration and effectiveness (Riddervold and Rieker, 2024; Mueller, 2024). As an illustration of this new reality in relation with the analysis in this paper, EU ammunition production doubled in 2024 compared to the previous year (Borel, 2024).

In the model, we assumed *perfect complementarity* between the visible (launcher) and invisible (ammunition) inputs in the production of military power. Using a neoclassical production function, involving partial complementarity and partial substitutability between visible and invisible inputs, would not change the main findings, provided that the output expansion path maintains a positive slope, which is the most plausible situation. In this case too low-budget states might seek to imitate the procurement strategy for visible weapons of high-budget states, which would trigger their over-investment behavior.

Despite its simple structure, our model contributes to the broader discussion about the nature of peace and conflict. Our findings reinforce the age-old wisdom that the belief in the end of conflict often sows the seeds of future conflict, while full preparedness for conflict is the best way to prevent it.

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