ei estudos internacionais • Belo Horizonte, ISSN 2317-773X, v. 10, n. 2, (jun. 2022), p. 42-58

Comparing the Effectiveness of Nuclear and Air-independent propulsion Submarine Fleets: a methodology for alternative force design choices applied to the Brazilian case

Comparación de la efectividad de las flotas submarinas de propulsión nuclear e independiente del aire: una metodología para las opciones de diseño de fuerzas alternativas aplicadas al caso brasileño

Comparando a Eficácia das Frotas Submarinas de Propulsão Nuclear e Independente do Ar: uma metodologia para escolhas alternativas de projeto de força aplicada ao caso brasileiro

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DOI: 10.5752/P.2317-773X.2022v10.n2.p42

Recebido em: 04 de fevereiro de 2021
Aprovado em: 20 de setembro de 2022

Abstract

This article proposes a methodology that enables one who has actual cost figures to perform the calculations for benefit-to-cost, strictly from the tactical and logistical standpoints, on the performance equivalence not of nuclear vs. air-independent-propulsion (AIP) submarines, but of nuclear v. AIP submarine fleets. With that in hand, it becomes possible for whomever might have sounder figures than what we could find about the complete life-cycle cost of either alternative to figure out, given our results about the benefit assessment, what would be the result of a benefit-to- cost analysis. We didn't perform the latter, due to uncertainty about the methodology by which the public available cost estimates were calculated. By providing a method for benefit calculation of the military worth of alternatives to support an assessment of the SSN/SSP fleet alternatives, we hope to have provided a sounder point of departure for debate, both in general terms, a method, and for the Brazilian case in particular, an application.

Keywords: fleet composition; force planning; strategic studies; Brazil; submarine

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RESUMEN

Este artículo propone una metodología que permite a quien tiene cifras de costos reales realizar los cálculos de beneficio a costo, estrictamente desde el punto de vista táctico y logístico, en la equivalencia de desempeño no de los submarinos nucleares frente a los de propulsión independiente del aire (AIP). , pero de flotas de submarinos nucleares v. AIP. Con eso en la mano, es posible que cualquiera que tenga cifras más sólidas que las que podríamos encontrar sobre el costo del ciclo de vida completo de cualquiera de las alternativas, averigüe, dados nuestros resultados sobre la evaluación de beneficios, cuál sería el resultado de un beneficio. análisis de costes. No realizamos lo último, debido a la incertidumbre sobre la metodología mediante la cual se calcularon las estimaciones de costos disponibles para el público. Al proporcionar un método para el cálculo de beneficios del valor militar de las alternativas para respaldar una evaluación de las alternativas de la flota SSN / SSP, esperamos haber proporcionado un punto de partida más sólido para el debate, tanto en términos generales, como para el método brasileño. caso en particular, una aplicación.

Palabras clave: composición de flota; planificación de fuerzas; estudios estratégicos; Brasil; submarino

RESUMO

Este artigo propõe uma metodologia que permite a quem tem valores de custo reais realizar os cálculos de custo-benefício, estritamente do ponto de vista tático e logístico, sobre a equivalência de desempenho, não de submarinos de propulsão nuclear versus de propulsão independente do ar (AIP) , mas de frotas de submarinos nucleares vs. AIP. Com isso em mãos, torna-se possível para quem quer que tenha números mais sólidos do que poderíamos encontrar sobre o custo do ciclo de vida completo de qualquer alternativa descobrir, dados os nossos resultados sobre a avaliação de benefícios, qual seria o resultado de um benefício. análise de custo. Não realizamos o último, devido à incerteza sobre a metodologia pela qual as estimativas de custo disponíveis ao público foram calculadas. Ao fornecer um método de cálculo do benefício do valor militar das alternativas para apoiar uma avaliação das alternativas da frota SSN / SSP, esperamos ter fornecido um ponto de partida mais sólido para o debate, tanto em termos gerais, um método, como para o brasileiro caso em particular, uma aplicação.

Palavras-chave: composição da esquadra, planejamento de força, estudos estratégicos, Brasil, submarino

Introduction

To what extent air-independent propulsion[3] (AIP) might offer a viable alternative to nuclear propulsion in submarines? Since life-cycle costs of nuclear-propelled attack submarines (SSNs) are so much more expensive than that of conventional submarines (including those with AIP, called SSPs), it becomes relevant whether SSPs could offer the strategic equivalent of SSNs. Ideally, this would be a matter of cost-benefit analysis, in that we would compare life-cycle costs of an SSN fleet and an SSP fleet of equal effectiveness. This is similar to the appreciation of weapons systems design (BROWN, 1990, on submarines e.g.). Our contribution is to some extent an expansion of that concern. For that, we weave the threads from technical considerations brought about by the different

[3] Three different AIP systems have been deployed: fuel-cell batteries, most notably in German submarines; MESMA (for *Module d'Energie Sous-Marin Autonome*) in French submarines, in which oxygen is cryogenically stored at low temperature and low pressure, to be mixed with the fuel in a combustion chamber, hot gases being exhausted at high pressures; and the closed-cycle/ Stirling engine. As hard as we tried to, we couldn't figure out how MESMA could match the discretion of the German fuel-cell system. Information on Stirling-engine submarines left us uncomfortable addressing it at the present time. We don't discard running a similar exercise on that alternative should that change. We chose to confine analysis to fuel-cell as a result. (EWING, 2011; ZIMMERMAN, 2000; BURCHER & RYDILL, 1994)

propulsion/energy systems of submarines and the tactical and logistical requirements for their performances, as might be put forth by broader political needs. We think that this interdisciplinary standpoint is the right one for designing a methodology for comparing force design alternatives, in this case, for a submarine fleet. This is an issue that may be relevant to many countries facing decisions about propulsion choices and submarine fleet size (ANDERSSON, 2015; LEONG, 2016; RASKA, 2016; COLLINS, 2020), as is the case of Brazil, which has a decades-long project for the local manufacture of a nuclear submarine.

Public figures for Brazil's nuclear submarine program costs do not discriminate among the costs of nuclear submarine *SN10 Álvaro Alberto* and the diesel-electric submarines being built by the PROSUB program[4]. Such figures as may be found (e.g., VILARDAGA, 2018; ROSA, 2018) do not account for crew, training, retirement/pensions, O&M costs, consumables, ammunition, nor, for nuclear-propelled submarines, monitoring, safeguards or decommissioning. This makes estimating life-cycle cost impossible.

Leaving aside non-strategic considerations (such as presumptive gains in prestige or status for developing indigenous nuclear technology or manufacturing one's own nuclear submarine[5], we focus *strictly and exclusively on strategic effectiveness* — tactical and logistical capacity and requirements to accomplish missions. A type-against-type comparison is insufficient. From a *tactical standpoint*, during a specific engagement, conventional submarines may have the advantage of discretion, over SSNs. Conversely, SSNs may have the advantage of speed in bringing about or evading an engagement. From a *logistical standpoint,* SSNs have the advantage of greater autonomy and sustained deployment speed. Consequently, type against type comparisons cannot support a satisfactory conclusion. Meaningful results depend on the appreciation of submarine *fleets*.

The point is that since the total life-cycle cost of any nuclear submarine is so much more expensive than that of a conventional one, including current AIP submarines, it becomes a relevant issue for defense policy and strategy, in terms of force planning, to know how many SSPs would be necessary to fulfill the same mission as against how many SSNs, and furthermore the logistical requirements of each option. Thus, a true comparison would be possible between force-design alternatives for SSN-only or SSP-only fleets in meeting strategical requirements. This is why we consider fleet-equivalence and not submarine-equivalence. We developed a model for submarine fleet operation, but circumscribed the scenario we take as an exemplar for presentation in this article. The scenario emanates from the Brazilian National Defense Strategy/Policy (BRAZIL, 2012; PROENÇA JR.& LESSA, 2017): submarine barrier interdiction of passage in the South Atlantic[6], patrolling an area some 700nm wide, about 3,000nm away from Rio de Janeiro for the duration of one calendar year – an exclusion zone in accordance with International Law, e.g.. This might be taken as the general formulation of the mission for submarine interdiction of passage in the South Atlantic beyond the range of Brazil's ground-based air power: (1) along the latitude of, say, Fernando

[4] Actually, the Brazilian Navy's webpage on Prosub (access in September 16, 2019) says that Prosub's "Phase B" (finished in 2017, according to the same page) would enable a final assessment of SN-BR (that is, SN-10 *Álvaro Alberto*) "total cost" (MARINHA DO BRASIL, s.d.), which implies that this total cost is still an unknown. For an overview, PADILHA, 2016.

[5] "Prestige" or "status" are addressed as a driver for Brazil's nuclear submarine program in POMPER & HUNTINGTON, 2005; CORRÊA, 2008; SÁ, 2015; SILVA & DE MOURA, 2016;; DAWOOD, HERZ & LAGE, 2015; for the broader context of nuclear policy, DAWOOD & HERZ, 2013; KASSENOVA, 2014a; for the issue of safeguards, IAEA, 1994; KASSENOVA, 2016; DINIZ COSTA, 2017; for the prospects of technological transfer, IZIQUE, 2007; GABINO, 2014. For an overview of the technological and industrial requisites and implications, MURRAY (2001); for a contrasting view of Brazilian activities as potential threats, NUCLEAR THREAT INITIATIVE, 2015.

[6] On South Atlantic maritime security, see DUARTE & KENKEL, 2019.

de Noronha, or; (2) a similar line offshore from Africa (the latitude of Dakar, e.g.), or; (3) the Strait of Magellan, or; (4) the Cape, or; (5) an oceanic approach to the *Pré-Sal* area (roughly corresponding to the Santos and Campos sea basins)[7].

It may well be that one might aspire for a more ambitious scenario, sustaining interdiction in more than one area simultaneously. For instance, one might consider that the "proper" scenario would be a line that closes off the entire South Atlantic from 200nm offshore of Brazil to 200nm offshore from Africa – say, Natal/Dakar at the narrowest, some 1600 nm. That's fine — just multiply the results presented for as many areas as desired. This is just a matter of what parameter one wishes to input. However, beyond the minimal scenario taken as an exemplar, these demands for "tous-azimuths" seem both inflated and, strictly speaking, very much beyond reasonable expectation, expressing strategic irresolution or a lack of political clarity of what are, or are not, the general outlines of Brazilian submarine-related defense scenarios.

This article identifies the size of SSN and SSP fleets that would provide equivalent tactical and logistical, hence strategic, effectiveness. The analysis leads to four interconnected "figures of merit" that provide an answer to what would be equivalent SSN/SSP fleets. Each figure of merit expresses the number of boats, X SSN = Y SSP through a given perspective: (i) tactical equivalence in the engagement; (ii) tactical and logistical equivalence in the fulfillment of the scenario; (iii) the logistical flow required to sustain that equivalence; and (iv) the size of the fleet required to meet that flow, which is the final number for effectiveness-equivalence. This might enable anyone who might have actual, *consistent, methodologically transparent,* figures about *life-cycle costs* to perform the meaningful cost-to-benefit comparisons that we couldn't.

All calculations are based on open-source information and we annotate authorial constructs to account for insufficient information. Therefore, we invite and welcome any better information so that we can improve either our model or the parameters of our calculations. Finally, we address the state-of-the-art c. 2020. We cannot account for major change in systems, material and procedural possibilities, e.g., a significant enlargement of the state-of-the-art in power storage.

We begin by explaining the differences between the different types of submarines; then, we work out the calculations while succinctly explaining the rationale for the four figures of merit for SSN/SSP fleet equivalence; finally, we share some concluding remarks on our methods and results. A technical appendix clarifies submarine power/speed calculations. In concluding remarks, we raise issues we would appreciate having discussed related to this approach as a methodological tool for force-design alternatives assessment.

Submarines[8]

A brief context for the issue might be this: thirty years ago (c. 1990), any prospective consideration for building an ocean-going fleet of submarines would have real difficulty in choosing diesel-electric (AIP was

[7] On the defense of the *Pré-Sal*, see OLIVEIRA, CEPIK & BRITTES, 2014. *Pré-Sal* defense would be within air range of Brazil: coastal defense. For a review of developments in onshore sea-denial options, WU, 2018.

[8] General information on submarine and anti-submarine warfare (ASW) is basically reliant on: AHMAD, 2011; BURCHER & RYDILL, 1994; CLARK, 2012; CHRISTLEY, 2007; CLANCY & GRESHAM, 2003; DEFENSE INDUSTRY DAILY, 2015; EWING, 2011; FONTENOY, 2007; FRIBOURG, ND; FRIEDMAN, 1984; GARDNER, 1996; GATES & LYNN, 1990; HERVEY, 1994; HUAN & MOULIN, 2010; HUBER, 2003; HUGHES & GIRRIER, 2018; IPPOLITO, 1990; KORMILITSIN & KHALIZEV, 2001; MILLER, 1987; MILLER & MILLER, 2001; POLMAR & MOORE, 2003; PSALLIDAS ET AL, 2010; RAGHEB, 2011; RAWSON & TUPPER, 2001; SPELLER, 2014; WAGNER ET AL, 1999; WHITMAN, 2010; ZIMMERMAN, 2000.

just beginning by then) over nuclear propulsion. That is not what is at stake here. The issue at hand is a matter of acknowledging the change in circumstances and appreciating its possible consequences and import. To whiz, to what extent the viability of air-independent propulsion, as brought up by the fuel-cell alternative (and thus, the prerequisites and peculiarities addressed below) would or would not lead to reconsideration of the option for nuclear propulsion, as the strategic importance of seas is increased (HAYNES, 2020).

As of 2020 there are three main types of submarines, classified by their power source: nuclear, diesel-electric, and diesel electric assisted by air-independent propulsion. Each type shares expectations of performance parameters and baseline acquisition and maintenance costs, which varies within type to particular classes of submarines. In the case of nuclear-propelled submarines, there is the additional cost of decommissioning, which can be substantial[9].

Submarines have two major functions: nuclear deterrence and maritime warfare. Nuclear-deterrence submarines' mission is deploying nuclear-armed ballistic missiles and are not addressed further. Maritime warfare submarines, nuclear-propelled or not, are called attack submarines and carry torpedoes, missiles or mines. While they may have a role in protecting or attacking nuclear-deterrence submarines or attacking targets on land, their primary purpose is to fight surface vessels (warships or merchants) and other submarines. The state of the art acknowledges general characteristics of attack submarines by type as follows. Nuclear submarines (SSN) use fission reactors to provide power with a fuel autonomy of years, being wholly independent of access to the atmosphere. Endurance at sea is limited by consumables and crew fatigue. SSNs are larger than the other types of submarines, facing difficulties when operating in shallow waters (French *Rubis* class, the smallest nuclear submarine ever deployed, length c. 73m, submerged displacement c. 2700 tons; US *Los Angeles* class, among the larger, length c. 110m, submerged displacement c. 6900 tons, e.g.). Nuclear reactors need constant cooling, and pumps' noise compromises stealth, particularly in shallow waters. Conversely, SSNs can better exploit differences of pressure and sound conductivity of different depths and layers in the open seas[10], managing cavitation[11] to preserve stealth while moving at speed. Thus, SSNs can move at their maximum sustainable speed (30kn+) at the price of degraded sensors and communications. A more cautious average speed of 20kn accounts for "sprint and drift", alternating maximum and minimum speed for detection, counter-detection and communications. On patrol and in the engagement, SSNs sprint and drift, change depth and position, managing cavitation to preserve stealth while maneuvering for advantage. Diesel-electric submarines (SSK), have diesel engines when they have access to the atmosphere to move and charge batteries, and batteries to power electric motors when submerged. SSKs' underwater endurance is a matter of energy management of a given battery load: the faster they move, the quicker they discharge their batteries. SSKs are expected to operate for "90 days", balancing fuel consumption, consumables

[9] A frequently mentioned figure is around thirty-eight million dollars for each submarine (RABKIN et al, 1992; KOPTE ET AL, 1996; KOPTE, 1997); Morrison (2011) updates the figures for FY-2010 US dollars, and reaches the figure of $37.2 million dollars for each SSN. For a complementary example, there is Coles, Greenfield and Fisher (2012) for the Australian assessment of monetary and non-monetary requirements of submarine construction.

[10] For sonar and sound propagation in water, and its implications for submarine operations, see DENNY, 2007; WAITE, 2002.

[11] "Cavitation" is the formation of a low-pressure zone around the propeller, which generates bubbles and therefore noise.

and crew fatigue. SSKs are smaller than SSNs, and maneuver more easily in shallow waters (German *U-209* class, length c. 64.4m, submerged displacement c. 1,810 tons is typical). They can run silent on motors, the utmost in stealth. However, as energy stored in batteries is limited, submerged SSKs manage energy expenditure both on patrol and in the engagement.

Air-Independent Propulsion submarines (SSPs) are diesel-electric submarines with an additional air-independent power source. Their size is comparable to SSKs, preserving the advantages of these, with the possibility of being independent of the atmosphere for some time (German *U-214* class, c. length c. 65m, submerged displacement c. 1900 tons, "3+ weeks" on AIP is allegedly typical). As of 2020, fuel-cell arrangements are such that they can be turned on only *once*, running down from then on: when to turn on AIP is a major aspect of SSP operation. Despite the additional "3 weeks" on AIP, SSPs endurance is also "90 days".

To sum it up: the farther the area of operations and the deeper its water, the greater the advantages of SSNs; in contrast, SSKs, fully charged, have the tactical advantage of superior submerged stealth; since SSPs can use AIP to remain submerged, they are more likely to have full batteries during an engagement than SSKs. With comparable life-cycle costs and superior performance, it's reasonable to expect SSPs to replace SSKs.

The four equivalences

What follows presents the rationale and the result of calculations that arrive at four successive figures of merit that address: the tactical equivalence in the engagement; the tactical and logistical equivalence in the fulfillment of the scenario; the logistical flow required to sustain that equivalence; and the fleet equivalence that maintains that flow[12]. We show how the four equivalences are calculated, but the exercise that arrives at a given value is more relevant than the actual figure. An actual figure is still useful because it expresses a documented reasoning open to criticism.

The model is simple: submarines depart from base, transit to, patrol and transit from the area of interdiction back to base. While on patrol, passive sonars of both SSNs and SSPs can detect ("hear") all surface targets and all submerged targets with a less than stealthy signature at many hundreds of nautical miles (all contacts are "targets" from a submariner's perspective). They endeavor to identify and track targets so as to get into engagement range, the distance from which they can reasonably expect to hit with their weapons, while seeking positional advantage. They manage speed, depth, relative position and stealth accounting for sound transmission, the noise they produce (the buckling of the hull as a submarine changes depth, the opening and closing of its torpedo or missile doors, and in the case of SSNs, the constant noise of pumps) and the sensor capabilities and maneuvers of the opponent. We begin with consideration of SSNs and SSPs once they have succeeded in interception and are within weapons' range of their target, dealing with *tactical equivalence in the engagement*.

[12] There might be some complementarity between our approach here and that outlined by Coyle (1983). In a sense, what is done here is to address, for nuclear and for AIP submarines, the "Needed versus Actual" and a part of the "Finding the Principal Flow Modules" (leaving aside the "New Ships Ordered" and the "New Ships Commissioned" flows) steps in Coyle (1983), and to simplify its "third behavioral flow" (related to maintenance and deployment) by reducing it to an estimated time frame; the "first behavioral flow" (related to crew) is also simplified by addressing only the training needed by available crews (and leaving aside the problem of creating a crew). This is a recurring concern, as in Buckingham (2009) and takes center point in the classic McCue (2008).

Tactical equivalence in the engagement

SSNs and SSPs may carry different types of torpedoes and missiles (and mines), each with different, but comparable, performance and requisites. Engagement range is the same for torpedoes (ranges in tens of nautical miles) or missiles (ranges over a hundred nautical miles), as actually releasing weapons requires sufficient proximity to have a *firing solution* with high confidence of hitting the target, accounting for the particulars of the target and of torpedoes and missiles: about 50nm. Both SSNs and SSPs rely primarily on passive sonar data to arrive at a firing solution that allows weapon release with the desired (or possible) degree of confidence in hitting the target, as other alternatives compromise their discretion leading to the problem of evasion. Releasing a torpedo or missile makes telltale noises ("transients"), and the firing plume of the missile compromises the submarine. Once weapons are away, the matter turns on whether it is advisable to begin evasion at once to "clear the datum" of where weapons were released, or if it is necessary (possible) to keep going to make use of torpedo wire guidance. (DENNY, 2007; WAITE, 2002; MILLER, 1987; HUGHES & GIRRIER, 2018).

At some point, evasion must take place, and the issue becomes whether it will be successful. Evasion depends on what, where and how the target and other opposing vessels can, or might, react having detected the submarine. Successful evasion may include coping with opponent response, breaking contact and escaping further detection. So, the issue in the engagement is the same for SSNs and SSPs: to arrive at a firing solution and evade opposing reaction.

SSNs are more likely to have the option of another attack after successful evasion. They can maneuver to return to engagement range, engage, evade, potentially until all weapons have been used or the mission accomplished – unless the opponent makes it so the SSN cannot re-attack. SSPs usually have only one attack. With batteries less than fully charged, re-attacking SSPs are at a disadvantage, and attempting to re-attack would correspond to the needs of a particularly high value mission. Acknowledging that the possibility of re-attack is always uncertain, as SSNs mail fail to do so despite their energy resources, and SSPs may seek it despite their lack of same, once in engagement range, there is no significant difference in effectiveness between SSN and SSP. Thus, the first figure of merit:

1 SSN-engagement = 1 SSP-engagement

Equivalence in Zones of Patrol (ZoPs)

Before the engagement, the issue is the difference of how far, and how fast, SSNs and SSPs can move to intercept, placing themselves in an advantageous position to engage. In our model, this is dealt with by having different-sized Zones of Patrol (ZoPs) that subsume the difference in speed and range of SSNs and SSPs, and thus the configuration of SSN- and SSP-ZoPs. A Zone of Patrol (ZoP) corresponds to the area where a submarine can detect, track and intercept passing targets. It is defined as a rectangle, X miles wide, Y miles long. To avoid friendly fire, there is only one submarine in each ZoP. The issue then becomes what are reasonable Zones of Patrol for SSNs and for SSPs.

Since the range of detection and tracking is greater than the range for interception, this can be left out as far as surface targets are concerned. As for submerged targets, detection and tracking ranges can be set aside as well, but for an entirely different reason. The relative stealth detection/tracking of sub-vs-sub is so idiosyncratic that a general model cannot hope to cope with it. A more refined, type-against-type under particular conditions model would have to be developed. As a result, the analysis of Zone of Patrol addresses only interdiction of surface vessels.

It all turns on the different performances of SSNs and SSPs in the approach, coming into engagement range (50nm) to attack with a reasonable expectation of success. Leaving aside the problem of avoiding detection, this is a simple navigational problem: distance, relative speed and direction of travel of submarine and target. In the scenario of barrier patrol, targets are necessarily incoming to the ZoP, and the matter is what size ZoP ensures interception for SSNs and SSPs.

Surface vessels can be expected to proceed at a cruising speed of about 15kn. Merchant-types have little capacity for bursts of speed, but warships can sustain bursts of 20-35kn. Speeds of 25-30kn are not sustainable over a long time except for nuclear-powered vessels, even if conventional warships can be expected to move as fast as they can if they suspect opposing submarines. Convoys – at least one merchant-type ship in the company of at least one warship – mean that interception must account for the slowest ship, while having to cope with the actions of the fastest. For the purposes of the scenario, if the submarine is detected in the approach and the issue becomes that of an engagement against the escort, it is unlikely that it will be able to attack its target. Therefore, it is paramount to remain undetected at least until weapons release, and even more so if the target is a warship. As the speed of a convoy is the speed of its slowest ship, the cruising speed of 15kn is what counts for interception.

This leads to the different sizes of Zones of Patrol (ZoP) for SSNs and SSPs.

For an SSN, the worst-case scenario is when the SSN is in one corner of the ZoP and the target is on the opposite corner. This would make an SSN-ZoP a rectangle with a diagonal of 1,000nm, otherwise the target might leave the ZoP altogether before it can be intercepted[13].

SN-10 is expected to have an underwater speed of 20kn. Most of the distance will be covered at 20kn to within 100nm of the target (easy air-range for helicopters), with tactical maneuvering from then on to the engagement range of 50nm. Thus, the approach at 20kn covers 900nm, taking 45 hours. Maneuvering in engagement range is the same for SSNs or SSPs, each making use of its own advantages. Considering that SSN evasion after the engagement might require separation beyond easy air--range (100nm) after weapons' release, this might admit 20h at 5kn (the worst case). As a result, the actions of one engagement would require 70 hours for the whole of approach, attack and evasion – roughly 3 days.

[13] It can be argued that a solitary SSN can pursue its target beyond ZoP limits as there is no risk of friendly fire. Certainly: however, this would mean rules of engagement in advance to "conduct unrestricted warfare", which does not accord with Brazil's policy preference. Attacks are only allowed in the ZoP (e.g. a politically defined exclusion zone).

The German *Type-212*, which stands for SSP, has a maximum underwater speed of 20kn. But the matter is not so simple, as submerged SSPs must manage energy expenditure. This is where some authorial analysis is required as to how SSPs would operate. In order to remain undetected, the logical course of action would be for an SSP to use its fuel cell on patrol as soon as it detects the incoming target (at hundreds of miles distant), keeping its batteries fully loaded for the engagement.

For *Type-212*, batteries would provide "8kn for 420nm" (Ewing 2011), approximately 50 hours underwater. Therefore, we need the following corollaries (see the Technical Appendix):

- at 8kn, each hour consumes 1/50, or 2%, of battery charge [original datum];
- at 16kn, power demand increases by a factor of 8, each hour consumes 8/50, or about 1/6, or 17% of battery charge;
- at 5kn, power demand decreases by a factor of about 4; therefore, each hour consumes 1/200, or .5%, of battery charge;
- at 4kn, power demand decreases by a factor of 8, which means that every hour takes 1/400, or 0.25%, of battery charge.

Therefore, we must work backwards to estimate the worst-case ZoP dimension for SSPs. To reach 100nm of successful evasion after attacking requires 20 hours at 5kn, or 10% of battery capacity. That means that, for what happens before evasion, there would be available at most enough energy for 378nm at 8kns. If we subtract 5 hours at 4kn for the engagement itself, it would consume 5/400, or 1.25% of battery capacity. That in turn would leave 370nm at 8kn, which is the most that can be spent for interception. This is the worst case, having to spend most of the batteries' charge to intercept. This allows estimating 370nm as the diagonal of the maximal ZoP for an SSP[14].

We would have a 370nm diagonal for an SSP ZoP, or 1/2.7 that of 1,000nm of SSN, which would give us the second figure of merit:

1 SSN-ZoP = 3 SSP-ZoP

Submarine flow to sustain ZoP

Getting any submarine "ready for sea in all aspects" meshes personnel, maintenance and supplies[15]. It calls for the welding of commander, personnel and systems into a well-crewed boat. Likewise, after its time on patrol, the boat gets readied once more. The issue is *time*: how quickly an outgoing submarine can get to the ZoP from its base and a returning submarine can return from the ZoP to its base.

For simplicity, availability and service of both SSNs and SSPs are assumed to be perfect, having no effect on the comparative effectiveness of the flow. So, it is assumed that there will be a submarine ready for sea when necessary, and the conditions to refuel, rearm and repair submarines as they return from patrol are always available, and further that refueling, rearming and repairing always allow submarines to operations after a fixed amount of time[16].

[14] It can be argued that more than one SSP could pursue the same target if it was close to the boundary of the ZoP and in range. Certainly: however, this would be risking friendly fire, which would have to be explicitly authorized in their rules of engagement in advance, and which does not seem compatible with Brazilian preferences – even if the opponent was not expected to have a submarine as part of the escort.

[15] See Coyle (1983, p. 890-894) for a different way of describing those needs, and McCue (2008) for the reciprocal actions they impose on belligerents.

[16] Coyle & Gardiner (1991) assumes a "fleet service" period of 16 months: a submarine would take 10 days to arrive at ZoP, spend 40 days there, return to base, go through a 15-day maintenance, and return to ZoP (which seems to presume both the speed and the two crews of an SSN, see below). After those 16 months, it would go to dockyard for 2-month maintenance, another 16-month time, then 4-month maintenance; a third 16 months, another 2-month maintenance; a fourth 16 months, and then a 2-year refit and maintenance time. After that, it would repeat this cycle twice more (fifth and sixth), then be scrapped. This applies to nuclear submarines in which refueling would require cutting the hull, and other rather complex maintenance in the absence of a hatch for refueling.

Once a submarine is ready for sea, it chooses a route and mode of movement compatible with circumstances. To get to ZoP, it moves in a way that makes it most difficult to be detected and tracked, some form of zigzag, increasing nominal distances.

SSNs can travel submerged all along, and at higher speeds, since they don't need to trade-off discretion for energy[17]. SSPs will need to charge their batteries — assuming the AIP system will be used during the patrol of the ZoP itself, in order to minimize the indiscretion rate (the ratio between the time that a submarine spends snorkeling and the total operating time) there. Every time a sub snorkels (or sails on the surface, which is unlikely), it compromises stealth, so it should travel submerged for as long as it could, but then it would travel at very low speeds.

Some compromise must be reached, and the typical pattern seems to be 12 knots submerged and 8 knots while snorkeling — which we *estimate*[18] would happen twice a day, for 30 minutes each time[19]. In the scenario we assume that any submarine, SSN or SSP, would proceed in zig-zag an average 30nm of deviation for simplicity, making the actual distance travelled 3700nm. The movement from the ZoP back to base is the mirror image of that from base to ZoP.

Travelling at 20kn, *SN-10* would take 7.25 days to reach ZoP and the same time to return to base: rounded up to 15 days total. Therefore, 2 SSNs sustain the ZoP over time, with alternating SSNs sufficient for the flow.

As for an SSP, assuming it snorkels for half an hour twice a day, its average speed would be: [(2 X .5h X 8nm) + (23h X 12nm)] / 24, or 11.8kn. So, an SSP would take about 26.5 days to reach ZoP and to return to base, rounded up to 30 days total. There is a margin of overlap in the flow (about 25%) but, as it is not possible to have fractional SSPs, 3 SSPs would be required to sustain the flow in one SSP-ZoP: roughly 1 each preparing/incoming, on station and outgoing/refitting.

One SSN-ZoP requires 2 SSNs in the flow; it takes 3 SSP-ZoPs to match 1 SSN-ZoP, and 3 SSPs in the flow for each SSP-ZoP, 9 SSPs in the flow to achieve equivalence. The third figure of merit is:

2 SSN-flow = 9 SSP-flow.

Fleet equivalence to sustain submarine flow

A submarine fleet is part of a polity's maritime force which enables the flow to come into being and to keep it going. This comprises submarines, installations and all else that is required so that force can be taken as a given.

SN10 is expected to have a hatch, so nuclear refueling and its problems are not an issue here. In practice, a matter of context, priority and preparation, an SSN could be resupplied as needed, in hours, and have enough consumables on board for a "180-day" patrol. An SSP would require more than that after a "90-day" patrol, as a result of the combined needs for maintenance (which an SSN is designed to postpone) and restoring the fuel cell. SSPs would seem to have to worry, above all, about how long it takes to restore AIP capability. Supply of consumables and

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[17] It is entirely possible to argue that there might be a scenario in which zig-zagging would be unnecessary, assuming no risk of detection or interference. That is a bold assumption, particularly once the scenario is running, although it might indeed be the case for SSNs in deep water transit.

[18] We arrive at this authorial estimate with unsatisfactory information.

[19] Weather, and thus season, may play a role in many ways.

munitions is trivial. Minor repairs and so on admit to rules of thumb of maintenance (around 30% of operating time), and while restoration of AIP capability is more problematic, the replacement of fuel cells from stocks, assuming perfect availability and serviceability, is trivial.

The main bottleneck for submarine turnover in fleet terms, however, is not materials or maintenance, but the rest and recovery of the crew. Specific requirements would be a function of the stress of a particular patrol, but the peacetime rule of thumb is 60 days. As this is longer than the time required for supply and maintenance needs, then 60 days for complete recovery and making ready to return to ZoP will do. SSNs may have two crews and admit returning to patrol very quickly once in port or having access to fresh crew and consumables: days if not hours. Each SSN can operate "180 days" at sea after which somewhat longer maintenance is required, but the scenario's duration of one year can be met with 2 SSN. A fleet of 3 SSNs with two crews for each ensures against the worst-case scenario of SSNs starting/being on their second crew run. SSPs have one-on-one association between boat and crew (this is a matter of design and necessity). Downtime for SSPs is 60 days, further constrained by the number of "slots" that correspond to facilities that carry material maintenance. Assuming this takes 30 days, if there is only one slot, there might be a waiting line of incoming SSPs or a corresponding stock of boat-ready but not crew-ready SSPs. This would then impact on fleet demand over the 9 SSP flow, presuming perfect scheduling, but this is not so bland a problem of queues. While the same caution used with SSNs might suggest a larger number of SSPs, the overlap of time in flow already considered makes it redundant: there is already about a 25% reserve in the number of submarines, obviating the need for fleet reserves at the price of managing the slack of the submarine flow. This is a matter of granularity: for 2 SSNs, a third boat is required; with 9 SSPs with 25% flow reserve, none more are required.

This leads to the fourth figure of merit:

3 SSN-Fleet = 9 SSP-Fleet.

It is important to stress the ratio is 3:9, that cannot be reduced to 1:3. For example, with 9 SSPs, the 25%-slack in flow provides an SSP reserve for the fleet; that would not be the case with 3 SSPs.

Throughout, the issue when one considers submarine fleets is that submarines cannot be held ready for sea for long. The process making ready for sea has a rhythm of its own, and while it can be speeded up or delayed to some extent (leveraging the 25% of SSP flow to the benefit of fleet, as above), it is not really possible to keep a boat "ready for sea" without cutting into its patrol time, even if it remains in port. To that extent, we presumed, for simplicity, that routine readiness provides boats to depart to ZoP at t_0 for a full patrol; but the model accommodates sensitivity analysis of readiness as required. The model also allows calculation of collateral attributes, like the number of "slots" a fleet must possess in order to provide sufficient crew, materials and installations to sustain the flow: 2 slots for every 3 SSPs, for example. But sensitivity analysis of readiness management or appreciation of collateral results are beyond the present article.

The model provides the fleet equivalence of SSNs / SSPs required to "generate one (1) submarine-set in ZoP and sustain it over one year". It also shows that less than 3 SSNs or 9 SSPs exemplify the slippery slope to the logic of "risk fleets" that might inhibit but may not effectively interdict.

Concluding remarks

In order to sustain interdiction in one given area, either a fleet of 3 SSNs or of 9 SSPs is required. The aggregate number of submarines for the maritime force as a whole would depend on the number of areas in which this would be required simultaneously, with commensurate logistical infrastructure. It is assumed that all submarines would depart from a single base; more bases would decrease the number of SSPs if transit times were reduced; facilities, in turn, would be increased. The model does not account for the indefinite continuity of the maritime force. That would be force planning beyond the submarine fleet of SSNs or SSPs. The life-cycle of systems installations or personnel are beyond the scope of what the article addresses.

The model took matters as they stand: the variables, parameters and units of measure considered are those used in maritime practice. Two aspects would benefit from criticism, and constitute our concluding remarks. The first is whether the variables and estimates the model addresses are comprehensive enough for the intended result, or if any relevant variables (or relationships) have been misperceived or overlooked. The second has to do with cost: are there sources for sufficiently robust variables, values and parameters for cost that would address this particular matter, and thus allow for a full effectiveness to cost analysis?

Further, there are aspects that need expansion related to sensitivity and robustness, as a model cannot provide for the unforeseen and happenstance, on two counts. One, on that of the risk associated with the life cycle of, in this case, boats and installations (the life cycle of personnel and materials being presumed dealt with by routine). Two, on that of the risk associated with catastrophic events: the accident or incident of the loss of a boat or installation (and as a subset of installations, stocks). The former admits to the specifics of a concrete scenario and belongs to the level of defense policy, that is, what explains the existence of the fleet itself as part of a polity's maritime forces over time – and is beyond the reach of the article. The latter is different, and admits to the counsel of prudence, its outcome being the result of a risk-benefit analysis, expressed in general terms as the provision of reserves.

The problem of reserves is borderline between fleet force-design and defense policy, regardless of how it is or it is not addressed. It is a matter of judgment, if it is or is not wise to have additional boats or redundant installations to lend resilience to the arrangement of the fleet. And in this case, it can be disproportionately expensive because of granularity and coupling: one SSN more is a hefty expense, as many SSPs as prudent the same, redundant facilities (and separate facilities, in this case) as well.

The specifics of submarines, Zones of Patrol, flow to and from bases and the configuration of fleet and infrastructure are but the particulars of a broader formulation. While this particular presentation benefits from the central role of a single weapons system, it would appear that it has possibilities of being generalized, with potential adaptation to combined-arms forces as well as joint forces. We hope to have provided a sounder basis for debate by the focus on fleets, on force-design, both in general terms, as an approach to effectiveness analysis in general, the seedling of a methodology, and for the case of Brazilian submarine choices in particular, an application.

This article proposed a figure for the size of nuclear-propelled (SSN) and air-independent (SSP) submarine *fleets* with equivalent effectiveness: 3 SSNs equivalent to 9 SSPs. The thrust of the article corresponded to four successive figures of merit that addressed the tactical equivalence in the engagement, the tactical and logistical equivalence in the fulfillment of the exemplary scenario described in the introduction, the logistical flow required to sustain that equivalence and the fleet required to maintain that flow. It presented the rationales and calculations that support the numerical results obtained, concluding with some issues we would appreciate being discussed that relate to our choices of variables and parameters, the availability of data for cost, and as well as to the utility of such an approach as a methodological tool for comparative assessment of force-design alternatives and as a contribution to the Brazilian defense debate.

Technical appendix

Submarine propulsive power demand admits the formula (Ippolito 1990):

$$P = 0.06977 \text{ X } Cd \text{ X } V^{2/3} \text{ X } v^3$$

Where P is power, 0.006977 in a non-dimensional constant, Cd is the drag coefficient of a given submarine, V is the volume of the submarine, and v is its speed. Change in power demand depends exclusively on changes in the submarine's speed. Since demand in power changes with the cube of speed, every time speed doubles, demand increases by a factor of 8; every time speed is halved, demand decreases by a factor of 8.

TABLE 1 — CUMULATIVE INCREASE AND INCREMENTAL VARIATION IN POWER DEMAND FOR SUBMARINES ACCORDING TO SPEED (IN KNOTS)

Speed (kn)	Cumulative Increase in power demand	Incremental variation in power demand
1	1	-
2	8	8
3	27	3,38
4	64	2,37
5	125	1,95
6	216	1,73
7	343	1,59

Speed (kn)	Cumulative Increase in power demand	Incremental variation in power demand
8	512	1,49
9	729	1,42
10	1.000	1,37
11	1.331	1,33
12	1.728	1,3
13	2.197	1,27
14	2.744	1,25
15	3.375	1,23
16	4.096	1,21
17	4.913	1,2
18	5.832	1,19
19	6.859	1,18
20	8.000	1,17

Source: Authors' calculations after Ippolito (1990)

Summary Table of Figures of Merit

Figure of Merit	**On application**
Tactical equivalence in the engagement	Number of SSN to SSP to achieve equivalent expectation of success in the engagement (1 SSN-engagement = 1 SSP-engagement)
Equivalence in Zones of Patrol (ZoPs)	Number of SSN to SSP to achieve equivalent covered area on patrol (1 SSN-ZoP = 3 SSP-ZoP)
Equivalent Submarine flow to sustain ZoP	Number of SSP to SSN to sustain equivalent effective presence in area of operations (2 SSN-flow = 9 SSP-flow)
Fleet equivalence to sustain submarine flow	Number of SSP to SSN to achieve equivalent availability over time (3 SSN-fleet = 9 SSP-fleet)

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