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Proposals for requirements definition in defense systems projects: an application in new cruise missile developments

Propuestas para la elaboración de requisitos en proyectos de sistemas de defensa: una aplicación en nuevos desarrollos de misiles de crucero

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Abstract: The paper presents proposals for definition of project requirements in defense systems, considering upcoming developments of cruise missiles as an application. Based on the Tomahawk missile history, the text recommends interactions between the project's sponsoring organization and development engineers with a process of adjustments and tailoring among the user's initial expectations, the technology readiness level (TRL), and national industrial skills. This task aims to provide in-depth analyzes and solutions to technically advise authorities in the decision-making process involving engineering projects related to the national defense strategy. In addition, the authors created a new type of requirement, the "zero requirements" It is characterized by an immutable demand from the main stakeholder, which decisively affects the product's final characteristics. Finally, the article proposes improvements in the requirements writing by adding new information fields to understand the user's initial goals better and provide an initial resource/cost/time-consuming estimation.

Keywords: project requirements, cruise missile, technical advice for decision-making, system engineering, Tomahawk.

Resumen: Este artículo presenta propuestas para la elaboración de requisitos relacionados con proyectos de sistemas de defensa, teniendo como aplicación práctica en los próximos desarrollos de misiles de crucero. Con base en la historia del misil Tomahawk, se recomienda la interacción entre la organización patrocinadora del proyecto y los ingenieros de desarrollo en un proceso de ajustes y adaptaciones entre la expectativa inicial del usuario, el nivel de desarrollo tecnológico y las capacidades industriales nacionales. Esta tarea puede brindar análisis en profundidad y soluciones para asesorar técnicamente a las autoridades en la toma de decisiones que involucren proyectos de ingeniería relacionados con la defensa nacional. Aún se crea una nueva clase de requisitos, los requisitos cero, que se caracterizan por contener una demanda inalterable por parte de la autoridad decisoria, afectando decisivamente las características finales del producto. Finalmente, se sugieren complementaciones al texto de los requisitos para comprender mejor los deseos del usuario y permitir prever los plazos y los recursos materiales, financieros y humanos demandados.

Palabras clave: requisitos de diseño; misil de crucero; asesoramiento técnico para la toma de decisiones; ingeniería de Sistemas; Tomahawk.

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1 INTRODUCTION

Project requirements are attributes in a system. They consist of simple sentences that identify the capacity, characteristic, or quality level of a system and are designed to add value or present utility to the user (or client) (YOUNG, 2003).

They also provide the main foundations that enable a development team to define all the other associated technical work in the course of a project, that is, the development of the concept, study of feasibility, development of the solution, manufacture of prototypes, performance of engineering tests and tests necessary to prove each of these project requirements (INTERNATIONAL COUNCIL ON SYSTEMS ENGINEERING, 2015; UNITED STATES, 2020a).

In the development of defense systems, each user's need registered as a project requirement (whether technical or operational requirement) demands a certain level of technological maturity (Technology Readiness Level – TRL) (UNITED STATES, 2020b) necessary for the implementation of the final solution. The process of developing the set of requirements must therefore consider the technologies mastered by the national industrial base and the total resources made available (financial, human, material, etc.) (UNITED STATES, 2001). Thus, weighing and selecting characteristics/functionalities among options that prioritize the rapid acquisition of a military employment material (MEM) or the acquisition of knowledge and capabilities still absent in the country's industrial park (LIMA, 2007), which usually requires more time, is possible.

Note that these factors are interrelated and, in practice, require that the project requirements be elaborated in an interactive way in a process of adaptation and adjustment between the initial expectation of the user and the technological scenario of the country (NATIONAL AERONAUTICS AND SPACE ADMINISTRATION, 2017), having as decision variables the time available to obtain the defense system and the available resources (or the size of the effort that is intended to be expended) (UNITED STATES, 2001).

This fact requires, preferably before the decision to start the development, a joint work between the user (or the sponsoring organization) and the engineers/managers of the project (UNITED STATES, 2020a). An engineering technical team, experienced in the subject of interest, can identify limiting factors and obstacles in each potential requirement (initial need/desire) (RICH; JANOS, 1994). The objective is to supply the sponsor with information that allows him to visualize the general scenario, advising him in making decisions that involve the definition of the best way to obtain what was intended, either with adaptations in the requirements initially proposed (path with priority for shorter obtainment time and/or lower cost), or by preparing auxiliary projects whose results are fundamental in the main project (path with priority for the object to be developed, regardless of the time frame, the technological capacity available, and the resources required).

The importance of this joint work is evident in the development of smart munitions, especially tactical cruise missiles, since integrating different systems and subsystems in a manufacturing environment that is specific and dedicated to this purpose is required (FLEEMAN, 2012). Many of these complex components may be available only in foreign countries, and problems such as trade embargoes may prevent or delay a national enterprise (GALDINO; SCHONS, 2022). Such issues may justify a strategic approach, with the opening of an auxiliary project for the national obtainment of an item not yet technically mastered or not manufactured by the country's industry (UNITED STATES, 2002, 2022b).

In Brazil, so far and based on the experience of acting in smart munitions projects in the Brazilian Army, developments with an initial interactive process between the sponsoring body of the enterprise in the Brazilian Army and the engineering team of the project with the ultimate goal of elaborating the total set of requirements are not foreseen (LIMA, 2007; BRAZIL, 2022), and thus not customary.

The lack of interaction in the initial phases of innovation processes is one of the challenges to be overcome within an effort to implement a culture with a synchronous, systemic, and integrated vision of the cycles of technological innovation and life of a Defense Product (PRODE) (BARBOSA; BUENO CALDEIRA, 2021). The expansion of the interrelations between the agents of innovation is beneficial to the Defense Industrial Base, which would consequently bring the growth of the country's deterrent power (FRANCO AZEVEDO, 2018).

The absence of interinstitutional partnerships is a gap that still constitutes an obstacle to military innovation (BARBOSA; BUENO CALDEIRA, 2021). This article aims, therefore, to contribute with an increase in the interaction between the sponsoring agencies and the developers in innovation cycles of factors that generate military capabilities. The aim is to propose a specific class of requirement, whose data are established jointly and in common agreement between the operational user and the engineer's corps, still in the early phase of the military innovation cycle. And since this class of requirement is unnamed in the literature, this article proposes and adopts the term zero requirement.

The intention is that the zero requirement to represent only PRODE operational requirements that cannot be changed or eliminated, even in the face of challenges of a technical, commercial (embargoes, for example), or manufacturing nature, and that must prevail over all others. These definitions will allow a better understanding of the material to be developed and a more accurate provision on the costs involved, the efforts required, and the deadlines demanded.

The final wording of each zero requirement will be reached with the help of increased interactions between those responsible for establishing the primary operational desires and those whose task is to convert these mandatory needs into engineering language, with the consequent identification of viable technological solutions and establishment of the physical or performance characteristics necessary for the defense product.

Once this initial interaction is completed, obtaining, in subsequent moments, the production of the document with the total set of project requirements (operational, technical, logistic, and industrial), as already established in the General Instruction of the Army (BRASIL, 2022), is possible.

To deepen the topic, section 4 of this article addresses the elaboration of zero requirements for smart munitions, in particular, cruise missiles, and identifies the relevant categories. Section 5, in turn, presents the importance of ordering these categories according to attainment priority. Section 6 illustrates which fields of information must be filled in for each zero requirement. Section 7 has the final considerations.

2 BIBLIOGRAPHIC REFERENCE

2.1 History of cruise missile development – the Tomahawk missile

The proposal to establish a new class of requirements, the zero requirements, has its importance illustrated in the history of the development of the American Tomahawk cruise missile.

In 1972, SALT I (Strategic Arms Limitation Talks), a set of bilateral conferences and international treaties between the United States and the Soviet Union, established restrictions aimed at curbing the advance of the use of ballistic missiles with nuclear payloads. In addition to the context of nuclear war, the United States were concerned regarding the advancement of Soviet technologies related to anti-ship missiles and the use, in Vietnam, of remotely piloted aerial vehicles capable of gathering intelligence on hitherto inaccessible or highly defended areas (ROCKET AND MISSILE SYSTEM, 2015).

Including another type of weaponry capable of dealing with new enemy threats and of circumventing the growing obstacles imposed by restrictions of international agreements was clearly needed. The U.S. efforts in this direction occurred in 1970, when the concept of a strategic cruise missile (high range), with submerged launch, was demonstrated as feasible after a study conducted by the Center for Naval Analysis (CNA) (WERRELL, 1998). The United States had an extensive fleet of nuclear ballistic missile submarines (SSBN) in addition to attack submarines (SSN), both vital weapons in the struggle for dominance of the sea during the Cold War (1946–1991) (POLMAR; MOORE, 2004).

Despite a proposal to develop a long-range version of the Harpoon anti-ship missile, due to a greater ease and speed in obtaining it, an alternative program was proposed in 1971, the Submarine Tactical Anti-ship Weapon System (STAWS), aiming to design a missile with a range of 500 miles (800 kilometers (Km)). In 1972, a new name was assigned to the development by Secretary of Defense Melvin Laird, STAWS was renamed the Submarine-Launched Cruise Missiles (SLCM) (YENNE, 2018).

At the beginning of the SLCM program, only submarines were considered as means of launch. Multiple options were debated to define how cruise missiles would be stockpiled and primarily launched horizontally (via torpedo tubes) and/or vertically (in the same way as a ballistic missile). There were also debates about building a new class of submarines or adapting the fleet's attack and ballistic missile submarines. The decision came from Admiral Hyman Rickover, considered the father of the nuclear-powered Navy. The new cruise missiles would be launched from the torpedo tubes of existing submarines. This decision alone immediately limited the diameter of the new missile to 21 inches (533 millimeters (mm)) and the overall length to about 20 feet (6,096 mm) (YENNE, 2018).

After reviewing different developer proposals, the U.S. Navy selected two companies as finalists, each with different technical solutions. Convair, a division of General Dynamics, built a prototype (Figure 1) under the designation YBGM-109. Ling-Temco-Vought produced a demonstrator called the YBGM-110. The winner was Convair, and its YBGM-109 was successful during two launches aimed at evaluating the submerged launch with the subsequent transition to cruise flight. The YBGM-110, however, failed during the wing-opening process (YENNE, 2018).

Figure 1 – During the testing phases, the Convair prototype was known only as the General Dynamics Cruise Missile.

Source: Yenne, 2018.

However, the objective of this article is not to tell the origins of the Tomahawk cruise missile, but rather to extract important decisions made at the time and convert them into activities that advocate the interaction between operational agents and technical agents, still in the initial phase of the military innovation process, to improve the national development projects of new defense technologies.

2.2 Aspects of the administrative model of the life cycle of military employment materials in the Brazilian Army

Currently, the Brazilian Army manages the development of military employment systems and materials based on a General Instruction (EB10-IG-01.018) (BRASIL, 2022), whose purpose is to order and describe the processes, activities, and events that occur during the life cycle of the material (not only those to be developed, but also those already developed at the initiative of third parties), fixing the order and the responsible bodies.

According to this General Instruction, after identifying a demand to fill a gap or maintain operational capacity, the Operational Direction Body begins, with the doctrinal production cycle of the Land Military Doctrine System, to elaborate a document called Doctrinal and Operational Conditioners of a Military System of Defense of the Land Force (CONDOP SMD F Ter), which should describe the doctrinal and operational aspects, such as: mission, the operating environment, the types of operation, the functionalities to be performed, the expected performances, the necessary logistical support, and the technological, material or human constraints that may limit the operation.

This action foreseen in EB10-IG-01.018 is adherent to what is desired from the point of view of development engineering, that is, the first step when starting a project of a new defense system should be to know and understand the initial desires of the sponsoring organization of the enterprise (UNITED STATES, 2020a).

The steps aimed at analyzing project requirements impose significant challenges both for the agency that will stipulate its operational needs and for those responsible for the system engineering of the project, and deficiencies in this process cause delays in the enterprise and greatly increase its cost (PIASZCZYK, 2011). In addition, inadequate wording of requirements, whether from ambiguities or the erroneous definition of functionalities or characteristics, affects all subsequent engineering and project planning activities (CLARK; HOWELL; WILSON, 2007).

Thus, preparing the CONDOP SMD F Ter with the participation of the engineers who will act in the new development, supplying them with specific information that allows them to already draw the first estimates of costs, deadlines, and necessary material and human resources, is recommended, in addition to enabling the beginning of the writing of the technical, logistic, and industrial requirements.

With reference to the Tomahawk's track record, one clearly observes the initial motivation of the United States to fill a gap in its operational capability: international agreements that limited the use of its nuclear arsenal and the emergence of new enemy weapons systems. The decision of the US high command was to develop an ammunition that, despite having existed since 1918 in rudimentary versions (YENNE, 2018), would need to have a range with dimensions that would enable its use at the strategic level (WERRELL, 1998).

In this case, two important points for consumption of development engineering are identified. The first is prior knowledge of gaps in operational capability (or the facts that prevent its maintenance). The concept of operational capability is related to the attitudes that units must have oriented to obtaining a strategic, operational, or tactical effect, usually by combining personnel, instruction, training, equipment, logistics, and organizational structure, based on an employment doctrine (BRASIL, 2015).

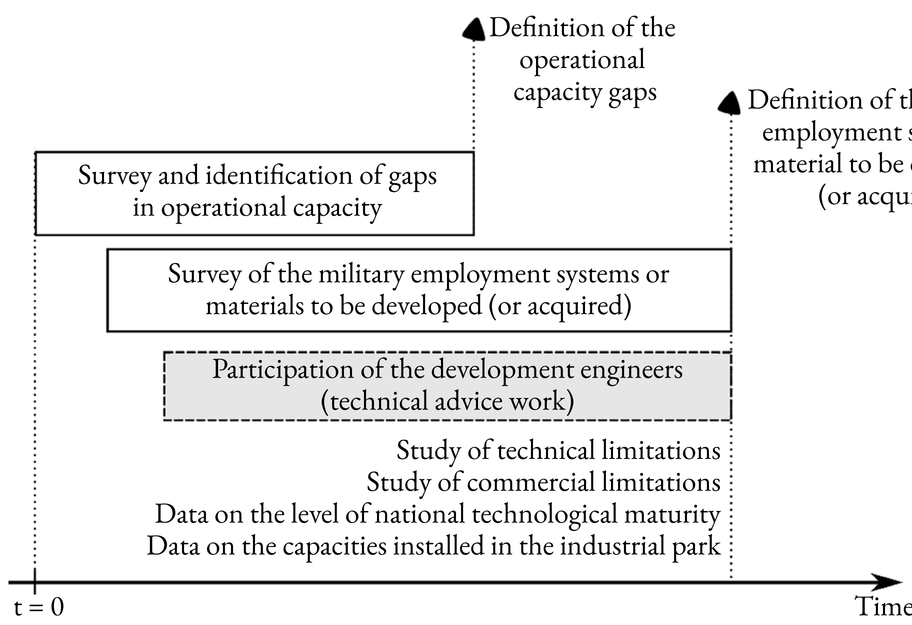
The other point is to be aware of the options preliminarily identified as solutions (military employment systems or materials). Both enable a group of experienced engineers to contribute new technical propositions or feasibility analyses (RICH; JANOS, 1994) and, in a joint debate with the sponsoring organization, establish the most appropriate type of material, having already considered possible technical limitations, the level of national technological maturity, and the capacities installed in the industrial park (GIRARDI; FRANÇA JÚNIOR; FERREIRA GALDINO, 2022; UNITED STATES, 2002).

It is an interactive work with the purpose of advising the decision making regarding the type of material or system to be developed, promoting initial estimates of the technological needs and the costs/deadlines involved.

Similar dynamics were observed when the Center for Naval Analysis (CNA), about two years before Admiral Hyman Rickover's decision to use submarine-launched cruise missiles, conducted engineering studies to verify the feasibility of launching this type of ammunition when submerged. The CNA is a research organization comprised of a cadre of experts with training and experience in the field of defense that serves the public interest by providing in-depth analysis and solutions to assist U.S. government leaders in choosing the best path in defining policy and managing U.S. defense-related operations and projects (CNA, 2022).

Therefore, we infer that in projects for the development of complex defense systems, a temporal division is recommended in the work of surveying and identifying gaps in operational capacity and of surveying options of military employment systems or materials to be developed or acquired (Figure 2). Thus, to contribute to the increase of interaction between the agents of innovation still in the initial phase of the enterprise, the participation of an experienced and cohesive team of engineers alongside the sponsoring organization is suggested to assist in the work of selecting the military employment system or material to be developed.

Figure 2 – Illustration of a way to increase the interaction between the agents of military innovation, by including of the participation of a team of development engineers still in the phase of survey and identification of gaps in operational capacity and survey of options of systems or materials of military employment to be developed (or acquired).



Source: Figure elaborated by the authors, 2022.

A complementary use of the dynamics illustrated by Figure 2 is carrying out the documentary record of the gaps found in the operational capacity, since those are important raw materials for elaborating the technical, logistical, and industrial requirements in subsequent stages. In smart ammunitions projects, some examples of these gaps are: (i) the means of launch (in the case that resulted in the project of the Tomahawk, there was until then no possibility of launching cruise missiles when submerged); (ii) certain targets that need to be neutralized (warships or strategic targets such as bridges, airfields, refineries); and (iii) a certain region of the national territory with the possibility of improvement in the defensive system (distances between potential targets and launch points, and the peculiarities of the operational environment). Note that a gap may also turn out to be the absence of national mastery of a specific technology, such as a certain type of warhead or internal component of the ammunition, such as electromechanical actuators, inertial systems, or cruise motors.

An example of documentation (registration) that condenses operational gaps filled with the help of the use of cruise missiles is the study on an anti-access and area denial strategy at the mouth of the Amazon River (CALDAS, 2020). Just by way of brief illustration, the reading of the research, under the focus of engineering, makes it possible to extract climatic conditions and define the respective applicable technical standards, establish criteria and logistical solutions for displacement and storage of the system/ammunition, and understand the nature of the targets, with all the consequent determination of necessary characteristics of ammunition performance.

3 THE CREATION OF ZERO REQUIREMENTS AND THEIR CONTRIBUTION TO INCREASED INTERACTION BETWEEN MILITARY INNOVATION AGENTS

From the point of view of an engineer in the technical leadership/management of a new project, the beginning of the development of a smart ammunition requires the knowledge of specific data provided only by the client (or sponsoring organization). These are operational constraints that, under no circumstances, can be removed or changed, even in the face of technical, manufacturing, or commercial challenges (embargoes, for example).

Although in a first reading these impositions provided by the operational agent (client) can be interpreted only as the already existing operational requirements (BRASIL, 2022), the experience in projects of development of complex defense systems (REZENDE *et al*., 2021; REZENDE *et al*., 2022), such as cruise missiles and guided rockets (FLEEMAN, 2012), shows the indispensability of understanding, recording and classifying specific constraints that represent operational requirements, imposing restrictions on the developer and determining the aspect, cost, and time frame to obtain the product (BOORD; HOFFMAN, 2016; KRILL, 2001).

The process that culminated in the development of the Tomahawk missile evidences one of these immutable constraints under any conditions. Despite any other operational requirement, the new missile should have the dimensions of the torpedo tubes of the submarines of the United States Navy (YENNE, 2018). And this characteristic could not be changed, even in the face of any technical difficulty.

This example illustrates the repercussions from the engineering perspective. Some project variables, for example, the range, the volume available for fuel, and the payload capacity, would suffer direct impact (FLEEMAN, 2001) and would have their values defined or limited only based on a single operational imposition. Not to mention the very possibility of failure of the enterprise, which would be noticed only at an advanced stage of development, if this imposed operational condition required effort (material, financial, technological, etc.)

above what was possible and was included only in the set of all other operational requirements, as executed, so far, in the developments of the Brazilian Army (BRAZIL, 2022).

Immutable operational impositions are common in the project of new systems or materials for military employment. Such as one of the Basic Operational Requirements of the Tactical Cruise Missile System for the Brazilian Army (BRASIL, 2012), which establishes that ammunition must be launched from the Multiple Launch Vehicle (AV-LMU) that integrates the ASTROS system (ASTROS, 2021; OLIVEIRA ALVES, 2022), from the company Avibras. This single requirement immediately restricts the maximum length of the ammunition (the limit is equal to the length of the AV-LMU launch platform) and, consequently, may make it impossible, during the execution of the development project, to achieve several other operational requirements related to performance or functionality, such as the range and warhead capability (FLEEMAN, 2001). In extreme cases, the outcome will be the impracticability or reduction of previously desired operational capabilities, a fact that often occurs in the innovation of defense systems (UNITED STATES, 2008).

Having as a good practice sample in obtaining defense products the initial development process of the Tomahawk missile, in which the interaction between agents of innovation provided the execution of early feasibility and engineering studies on immutable operational impositions, and allied to the impacts that specific requirements of defense systems can have on obtaining the defense product (PRODE), a new class of requirements is established, called zero requirements.

Thus, the challenge lies in the prior identification of the constraints that will be the basis for the entire construction of the engineering project (zero requirements). An interactive work between the operational decision-makers and the team of development engineers is recommended to evaluate the customer's requests with high potential impact on the engineering solution (evaluation of the effects of interrelationship between requirements arising from the operational aspect). This action also brings as a benefit the increase in interactions between operational and technical agents in the early stages of the military innovation process.

Up to this point, we infer that different defense systems have their specific operational constraints that are more likely to be imposed and have a high risk of affecting all other engineering decisions and solutions throughout PRODE development.

To deepen the proposal for the creation of zero requirements, its concept is expanded in the following sections considering the case of a defense system characterized by cruise missiles, with the survey of its main categories to be debated in the process of interaction between the agents of innovation. The importance of the correct relative ordering between the zero requirements and the set of information to be incorporated into their text will also be addressed in this article.

4 ZERO REQUIREMENTS FOR CRUISE MISSILES

In the case of cruise missile developments, we propose to separate the zero requirements into the following categories: means of launch, range, target types (and destruction/neutralization effects), accuracy, performance constraints, countermeasures, logistical aspects, and critical technologies.

4.1 Means of launch

The means of launch category should contain all the forms envisaged for the launch of the new missile, be they land, sea, and air. The way a missile is launched is one of the main variables of change in the appearance and geometry of the ammunition (FLEEMAN, 2001), and, therefore, is a typical zero requirement. The cases of munitions with multiplatform launch forecast require several adaptations in their fuselage and in the launcher receptacles (containers or canisters). For the launch from the air, for example, it should be provided for the insertion of support handles for fixing the missile to the pylons of the launching aircraft and localized structural reinforcements, all of which increase the weight and change the internal volume of the missile. The unintended consequences are a shorter range and/or reduced payload capacity, based on the same geometry.

Figure 3 – Launch of the RGM-84 Harpoon (anti-ship missile), from a canister aboard the battleship USS Leahy.

Source: Yenne, 2018.

4.2 Range

The range category is one of the main operational requirements that characterizes a smart ammunition. Despite being commonly interpreted as the distance from the launch point to the target, the range has, for aerial vehicles such as cruise missiles, a strong dependence on the flight profile (flight trajectories, speeds, and altitudes). Therefore, the numerical value of the range should always be treated in conjunction with the operating envelope.

4.3 Target types (and destruction/neutralization effects)

Also highly relevant, the types of targets to be hit (and the expected effects of destruction/neutralization) directly influence various project decisions at both the technical/managerial and strategic levels. The choice for a particular target type impacts, among other factors, the selection of the terminal navigation sensor (seeker) and the warhead (high explosive, multiple, thermobaric, etc.).

Despite Brazil already having some initiatives to develop technologies related to seekers devices (TECNOLOGIA..., 2015) and finished products (active auto director radar) by a Brazilian company with the support of a foreign nation (OMNISYS, 2022), the need to shoot down certain types of target, alongside other operational constraints, may lead to the obligation to develop a new device, whose technology is not yet fully in the national domain.

In this context, project leaders and managers must act to create tasks that result in obtaining an adequate component, which can mean opening a project in parallel, with their own team and resources. This same strategic decision was made by the American company Raytheon (RAYTHEON, 2015), in preparation for the modernization process of the Tomahawk Block IV. Raytheon began an independent development of a new multi-mode seeker (Figure 4) to enhance the capabilities of the U.S. arsenal's main cruise missile.

Figure 4 – Captive flight test (2015) of the multimode seeker developed by the American company Raytheon. The seeker prototype was installed on a Tomahawk nose fixed to the front of a T-39 aircraft.

Source: Raytheon, 2015.

4.4 Accuracy

The term accuracy represents the degree of proximity of an estimate to the actual parameter. In terms of artillery weapon systems, accuracy means the probability of the ammunition's point of impact (estimate) reaching the actual target desired (real parameter). The term precision, on the other hand, means the degree of proximity of the observations to their mean. In the case of ammunition, we have the grouping of impacts in relation to their average, regardless of whether this grouping is close to the actual target (GUERRA; SANTOS, 2020).

Figure 5 – The circle on the left represents a high accuracy and a high precision. The circle on the right indicates low accuracy and high precision.

Source: Guerra; Santos, 2020.

Figure 6 – The circle on the left represents a high accuracy and a low precision. The circle on the right indicates low accuracy and low precision.

Source: Guerra; Santos, 2020.

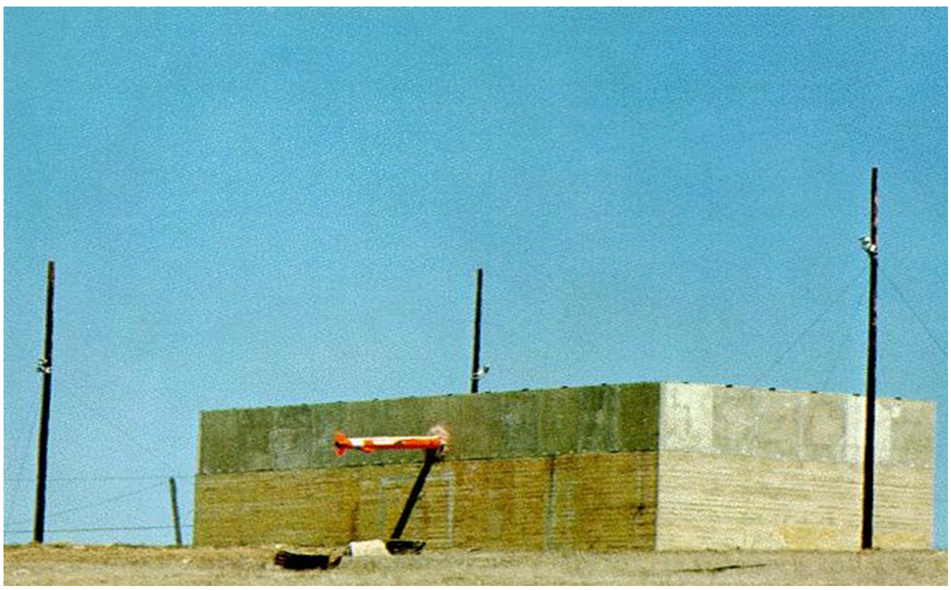
Another expression widely used by military operators and engineers dealing with weapon systems with ammunition use is the circular error probable (CEP). The basic concept of CEP lies in the fact that it is an estimator that informs the region in which they are expected to obtain 50% of the impacts after the employment of a weapon system.

The choice of a CEP value (or any other data on the accuracy of the ammunition) has a strong impact on the selection of internal components responsible for the correct positioning of the missile in its previously programmed trajectory, such as the inertial system and the terminal navigation system (seeker). The greater the need to ensure a drop point close to the target, the greater the requirement for highly accurate navigation sensors, which ultimately means adopting technologies with maturity levels considered low in Brazil.

On the other hand, adopting components manufactured by other countries has the possibility of leading to future trade embargoes and, at crucial moments of development, such as the final phase of product homologation tests for producing a pilot batch.

The option to achieve a certain value of accuracy may be linked to a strategic decision to start a separate development of technologies associated with navigation systems, with the mandatory approval and industrialization of the item.

Figure 7 – Flight test of the Tomahawk cruise missile launched from a submarine off the coast of California to a target in a United States Navy area located on the Island of São Clemente, California (NICKLAS, 2012).



Source: Nicklas, 2012.

4.5 Performance constraints

Performance constraints should be interpreted as imposing critical parameters for fulfilling the mission, in the various types of operation. Typical examples for cruise missiles are the minimum flight height and speed during cruise flight.

A missile intended to neutralize only warships already has its minimum flight height determined by the engineering solution, and the sponsoring organization has no need to establish a minimum value in its operational requirements (the necessary operational information is the target type, that is, the neutralization of warships of a certain class, for example). In this case, the flight height will be stipulated in technical requirements (the minimum flight height will depend on the state of the sea, to allow the flight profile close to the sea, or sea skimming).

For missiles intended to attack ground positions, minimum flight heights are related to the types of anti-aircraft battery or threat detection radars present during an operation, and values provided by the operational aspect will be used to adapt the engineering solution.

A similar situation occurs with cruising speed, making it more useful for the developer to understand the operational scenario than to obtain a numerical speed data.

Other examples of performance constraints are the requirement to operate in a GPS-denied space and the use of a certain constellation of satellites for communication between the ammunition and the ground station (route changes or applying mission abort commands). Note that such constraints also involve the use of technologies not yet fully established in Brazil, for example, high precision inertial systems and anti-jamming[1] GPS devices.

4.6 Countermeasures

Several countermeasures were developed to neutralize cruise missiles en route to the target. The RAND Corporation (SPEIER; NACOUZI; MCMAHON, 2014) summarizes the main countermeasures created to neutralize the threat posed by missiles, in their work on ways to deter the proliferation of this type of ammunition in the world.

The main performance variables related to protecting a cruise missile in flight are: flight altitude, trajectory (maneuverability), speed, and stealth level (JOHNSTON, 2000), which is associated with the radar cross section (RCS) and infrared signature.

Note that only one of these aspects, the cruising speed, directly stipulates the type of motorization to be installed or developed. Cruise missiles with supersonic speed around Mach 3 generally adopt ramjet engines (FRY, 2004), which, alongside scramjet engines (hypersonic speeds, above Mach 5), have not been finalized in Brazil. Therefore, an operational imposition for a cruising speed above the speed of sound will necessarily bring an increase in time and costs for obtaining a new engine.

Similarly, the levels of stealth directly influence the aspect of the final solution, either with application of radiation-absorbing material to the body of the missile, or by the design of the fuselage with facets aimed at reducing the radar signature.

4.7 Logistical aspects

Munitions with a high technological degree require a specific logistics, composed of a complex support system, even in times of peace (DANTAS, 2021).

Some logistical aspects have a high potential impact on the final solution of a new missile and should be addressed and incorporated into technical discussions in the early stages of development. Just as an illustration, the frequency required between maintenance activities (time interval in which the ammunition is removed from the magazine and moved to perform any overhaul or maintenance procedure) is mentioned; the use or

1 Anti-jamming GPS devices protect GPS signal receivers from intentional interference (jamming).

suppression of portable testing equipment (diagnosis of electronic and mechanical systems to verify that the missile is fit to be launched); the type of fuel used in the cruising engine; and the requirement that ammunition must remain inside the launcher container throughout the life cycle of the material.

Thus, considering logistical factors as zero requirements is also important.

4.8 Critical technologies

An operational gap may turn out to be the absence of national mastery in certain technology adopted in military employment systems or materials. For smart munitions, Brazil still needs to make advances in the homologation and industrialization of inertial navigation devices and terminal navigation systems (seekers – active, semi-active, and passive). Developments in engines to enable supersonic (ramjet engines) and hypersonic (scramjet engines) cruising speeds are also noteworthy, as well as advances in the production of such as thermobaric weapons.

Naturally, such work will require higher costs and, mainly, time, and it is up to the sponsoring organization to decide to develop critical technologies.

The development of cruise missiles suffers several restrictions, either from unilateral trade embargoes of nations that have critical components (engines, inertial devices, etc.), or by export control mechanisms of items listed as prohibited in international agreements, such as the MTCR (Missile Technology Control Regime) (MISSILE TECHNOLOGY CONTROL REGIME, 2022). Note that the emergence of the Tomahawk missile was due to a restriction imposed by one of these agreements (SALT I), which limited the use of the US nuclear arsenal.

Once the zero requirement categories have been elucidated, they can be summarized in a single table with hypothetical examples (Table 1). The numbering "0.?" shown in Table 1 indicates the proposed symbol for this requirement class. The "0" represents that this is a zero requirement and the marking "?" indicates that after selecting the operational impositions, they should be ordered in a priority criterion.

The examples in Table 1 aim to illustrate that a certain operational imposition in a certain category automatically exempts from filling out another (marked as unassigned). By establishing a constraint of sinking warships, accuracy and countermeasures become immediate consequences, and it is up to the developers to draft the associated technical requirements. Also, completing all categories is not obligatory, only those that represent an operational requirement that cannot be changed, despite any other operational requirement or technical, manufacturing, or commercial difficulty (in the case of Table 1, no constraints was assigned to the logistical aspect category). However, always informing if the sponsoring organization accepts the use of imported COTS components or if there is an interest in the use/development of only domestic items (critical technologies category) is recommended.

Table 1 – Zero requirement categories for cruise missiles and hypothetical examples.

Zero requirements for cruise missiles		
Numbering	**Category**	**Example**
0.?	Means of launch	Launch of the AV-LMU vehicle of the ASTROS system
0.?	Reach	200 Km
0.?	Target types (and destruction/ neutralization effects)	Sinking corvettes (similar to the Inhaúma class of the Brazilian Navy) and frigates (similar to the Niterói class of the Brazilian Navy)
0.?	Accuracy	Unassigned
0.?	Performance constraints	Unassigned
0.?	Countermeasures	Operating in a GPS-denied environment
0.?	Logistic aspects	Unassigned
0.?	Critical technologies	COTS (commercial-of-the-shelf) components can be used

Source: Table prepared by the authors, 2022.

5 THE ORDERING OF ZERO REQUIREMENTS

The origin of the zero requirements lies in the existence of immutable and guiding operational requirements for the entire ammunition development. However, since such requirements are established at a time prior to the formal start of the development project, situations in which compliance with one imposition makes it impossible, totally or partially, to comply with another may happen. Thus, an ordering between the zero requirements is suggested, based on the degree of inalterability of components associated with each category (Table 1).

This action aims to guide developers during solution feasibility studies (technical advice) and concept design. The intention is to report incompatibilities to the sponsoring organization, if they occur, and to present proposals for solutions aligned with priority operational needs, even before the start of development.

In the context of cruise missiles, typical examples of interrelated requirements are the range of the ammunition and the type of target it was intended to shoot down. The Tomahawk is a good element of comparison when looking at the ground attack (BGM-109C – Block II) and anti-ship (BGM-109B – Block I) versions, as shown in Table 2.

With the same dimensions and weight, the BGM-109B and BGM-109C versions of the Tomahawk show significant differences in range (Table 2). This lies in the need to employ, in the BGM-109B, a system (seeker) with radar technology to enable terminal navigation to moving targets at sea. Experience as a development engineer indicates that such devices have a high weight and occupy a large volume, factors that impair in-flight performance and limit the space allocated to fuel, respectively. Therefore, cruise missiles designed to neutralize moving targets tend to have a shorter range compared with those (similar) employed for destroying fixed (non-metallic) targets on the ground.

Table 2 – Comparison between range and target types for the Tomahawk, Harpoon, and Zvezda missiles.

Missile	Dimensions and Weight[1]	Range[2]	Target Type	Terminal Navigation System
Tomahawk (BGM-109C – Block II)[3]	L: 5.56 m D: 0.53 m W: 1,203 Kg	1,297 Km[4]	Fixed in the ground	Inertial + TERCOM + DSMAC
Tomahawk (BGM-109B – Block I)[5]	L: 5.56 m D: 0.53 m W: 1,205 Kg	465 Km[6]	Ships	Active radar
Harpoon (RGM-84F – Block ID)[7]	L: 5.3 m D: 0.34 m W: 785 Kg	240 Km[8]	Ships	Active radar
Zvezda Kh-35[9]	L: 4.40 m D: 0.42 m W: 620 Kg	130 Km	Ships	Active radar
Zvezda Kh-35U[10]	L: 4.40 m D: 0.42 m W: 670 Kg	260 Km	Ships	Active radar

1. The length of the missiles (without booster) is represented by the letter L, the diameter by the letter D, and the total weight by W. 2. Range values depend on the flight profile and speed. The data presented are based on typical values that characterize the ammunition. 3. Reference: Nicklas (2012). 4. Reference: Laur and Llanso (1995). 5. Dimensions and weight – Reference: Tomahawk... (2020). 6. Reference: Laur and Llanso (1995). 7. Dimensions and weight – Reference: RGM-84... (2016). 8. Reference: O'Halloran (2015). 9. Dimensions, weight, and range – Reference: Kh-35... (2018). 10. Dimensions, weight, and range – Reference: Kh-35... (2018).
Source: Table prepared by the authors, 2022.

The operational need for increased range on anti-ship missiles has been the subject of improvements from previous versions of the Harpoon. Introduced in 1991, the RGM-84F (Block ID) version enabled a range increase to 240 Km by increasing length to reach 5.3 meters (m) (O'HALLORAN, 2015) (previous versions, such as the RGM-84A has a range of 92.6 Km, with a length of 4.64 m (FULLER;EWING, 2016)). However, the version was discontinued in 2003, since the larger size limited the launch with the devices already in use by the surface and submarine fleet (O'HALLORAN, 2015).

Another relevant example of development aimed at improving range is the Russian Zvezda missile. The initial version makes it possible to shoot down ships 130 km away from the launch point, whereas the Kh-35U model allowed double this value, by replacing the cruise engine; reallocating the internal space for greater fuel storage; and using a new lighter seeker with greater sensitivity (Kh-35..., 2018). Thus, the external dimensions were not modified, maintaining the means of launch for both versions.

The previous cases demonstrate the importance of the sponsoring organization establishing an order of priority for the zero requirements. If there is a conflict of compliance between requirements, there are two possibilities to follow: the correction process (modification) occurs in items with a lower immutability index or the decision-making authority chooses, after technical advice based on feasibility studies, to change or suppress some zero requirement that causes the incompatibility. Based on the Zvezda missile, the means of launch assumes a higher rate of immutability (requirement 0.1) and thus has not undergone remodeling. The range requirement was met with changes in internal components of the ammunition (without alteration of the external dimensions).

With the example from Table 1, two fictitious scenarios are possible (Table 3). The first, scenario A, has the means of launch category with the highest immutability index (lowest possible numbering, i.e., 0.1), whereas the reach category has a higher numbering, for example, 0.3. The information provided by the decision-making authority indicates that any work to be carried out to ensure the desired range (or compliance with any other zero requirement) should not take place in the means of launch, but in another internal component of the ammunition (development of a new and specific fuel, change of the engine for models with lower consumption, structural weight reduction, etc.). Scenario B, in turn, lists the range category with numbering 0.1, which denotes the obligation to reach the required value, even if some adaptations are implemented in the means of launch, such as changes in the external dimensions of the ammunition (always with the proper authorization of the decision-making authority).

Table 3 – Examples of possible scenarios with different zero requirement orderings.

Scenario A		Scenario B	
Numbering	**Category**	**Numbering**	**Category**
0.1	Means of launch: ASTROS System AV-LMU	0.1	Reach: 200 Km
0.2	Target type: moving targets at sea	0.2	Target type: moving targets at sea
0.3	Reach: 200 Km	0.3	Means of launch: ASTROS System AV-LMU

Source: Table prepared by the authors, 2022.

6 THE WORDING OF ZERO REQUIREMENTS

The specialized literature in systems engineering recommends writing a project requirement as a simple sentence, expressed with the verb should, capable of informing the indispensable (characteristics or functionalities) to enable the development of a solution by the team of engineers (KOELSCH, 2016).

This article proposes to add four new information fields to the single, simple text that characterizes a requirement. The purpose is to provide additional data for a better understanding of the sponsoring organization's desires and expectations. The practice of working on smart ammunitions developments reveals that the process of defining and using the requirements is recursive and interactive with the decision-making authority, and data complementary to the text of the requirement contribute to reaching a robust final solution that adheres to the initial objectives of the sponsor. Thus, including the justification field is recommended, with a description of the motivations that led to the data present in the requirement.

Also, incorporating the fields test methodology (test method that should be used to prove the requirement), estimate of the number of specimens (prototypes necessary to prove the requirement), and basic acceptance criterion (criterion to evaluate the requirement) is suggested. This allows the technical leader of the project a better knowledge of the material and provides managers with a position on forecasting costs and deadlines demanded.

Table 4 was assembled to provide an example of how to fill in the proposed fields to complement the design requirements of defense systems.

Table 4 – Example of zero requirements wording with the inclusion of information fields.

Field	Content
Numbering[1]	0.1
Requirement[2]	The cruise missile is expected to be launched from the AV-LMU vehicle of the ASTROS 2020 system.
Justification[3]	Unlike other competing missile launchers, the cruise missile should be launched from the same platform on which the conventional rockets of the ASTROS system are launched, greatly facilitating the logistics of the missile, especially regarding the components of the launch vehicles[4]. Therefore, no changes should be implemented in the mechanical, hydraulic, and hardware systems of AV-LMU. Only software updates may be considered.
Test methodology[5]	Flight test.
Estimated number of specimens[6]	A functional prototype of the cruise missile.
Basic acceptance criteria[7]	Missile fulfilled all its functions (mechanical, electronic, etc.) after being fired from an AV-LMU vehicle in conjunction with the other vehicles of the ASTROS system.

[1,2,3,5,6,7] Prepared with the sponsoring organization and team of engineers. [4] Reference: Dantas (2021).

Source: Table prepared by the authors, 2022.

Although Table 4 presents an example of wording for zero requirements, the same procedure is recommended for all other technical, logistical, and industrial requirements of the project.

7 CONCLUSION

The task of developing requirements in complex systems development projects plays a vital role in obtaining a solid final solution capable of meeting the initial expectations and needs of the sponsoring organization. Experience in the development of smart munitions, such as cruise missiles, reveals that the greater the investment of time and resources in the process of building the requirements, the less the possibility of problems related to time delay and increase of the costs initially planned.

A significant addition to this process is the joint work between the user and the engineers/technical managers, even before the formal start of the development project. A team of military engineers, with experience in the subject of interest, can provide in-depth analyses and solutions to technically advise the authorities in decision-making involving engineering projects related to national defense.

For this purpose, an interaction between the sponsoring organization and development engineers is mandatory still in the phase prior to the elaboration of the CONDOP SMD F Ter.

The relevance of this constant joint work is also noted during the production of operational requirements, since they should, preferably, contain only information that characterizes the context of employment, avoiding, except in specific cases, texts with numerical data that may direct a specific technical solution, either to part or to the entire Military Employment System or Material (SMEM).

In this sense, adopting a new class of requirements aims to identify the constraints that will be the basis for all the construction of the engineering project. Given this importance, it is recommended that the zero requirements (and the relative ordering between them) be condensed into a document of their own, attached to CONDOP SMD F Ter.

Also, including new fields of information, adhered to the text of the requirement, allow a better knowledge of the desires and objectives for the SMEM, in addition to providing managers with an initial forecast of deadlines and material, financial, and human resources needed.

Finally, the proposals presented for elaborating requirements in defense systems projects contribute to achieving a final solution (SMEM) adhering to the initial operational demand, with estimated and more adequately controlled deadlines and costs.

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