Article

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Management of military systems: the role of technology readiness levels

Gestión de sistemas de material de empleo militar: el papel de los niveles de disposición tecnológica

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Abstract: The management of Military Systems (MS) usually involves a complex network formed by distinct actors with diverse backgrounds and cultures. In this context, to promote knowledge communication, integrate tacit knowledge, and understand stakeholders' perspectives is a challenge. The objective of this study is to investigate the management of MS from the perspective of Technology Readiness Levels (TRL), which standardize the common understanding and identify milestones of critical technologies maturation. Based on literature review and using as reference the Science and Technology Innovation System of the Brazilian Army (SCTIEx – *Sistema de Ciência, Tecnologia e Inovação do Exército Brasileiro*), this article shows that the TRL scale originally created for highly complex space technologies and systems does not meet the particularities of MS networks. Therefore, this article presents research questions raising important themes that, if explored, can contribute to the management of MS.

Keywords: Military System. Knowledge Integration. Technological Readiness Levels. Complex Product and Systems. Product Life Cycle.

Resumen: La gestión de Sistemas de Material de Empleo Militar (SMEM) normalmente involucra una red compleja compuesta por actores con formaciones y experiencias bastante diversificadas. En ese contexto, se convierte desafiador promocionar la comunicación del conocimiento, integrar conocimientos tácitos y entender las perspectivas de las partes interesadas para incorporarlas en las estrategias de gestión tecnológica. Este artículo tiene el objetivo de investigar la gestión de SMEM bajo la óptica de niveles de disposición tecnológica, que regula el entendimiento común e identifica marcos de la madurez de tecnologías críticas. Basado en revisión de la literatura y teniendo como referencia el Sistema de Ciencia, Tecnología e Innovación del Ejército Brasileño, este artículo muestra que la escala de niveles de madurez tecnológica, originalmente creada para tecnologías y sistemas espaciales altamente complejos, no atiende las necesidades de redes de SMEM. En razón de eso, son presentadas cuestiones en abierto, suscitando temas de investigaciones que pueden contribuir con la gestión de SMEM.

Palabras clave: Sistemas de Materiales de Empleo Militar. Integración del Conocimiento. Niveles de Disposición Tecnológica. Sistemas de Productos Complejos. Ciclo de Vida del Producto.

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1 Introduction

The *Sistema de Ciência, Tecnologia e Inovação do Exército Brasileiro* - SCTIEx (Science and Technology Innovation System of the Brazilian Army), whose central body is the *Departamento de Ciência e Tecnologia* - DCT (Science and Technology Department), is responsible for the teaching of Engineering, Research, Development and Innovation in the scientific and technological field of interest of the Brazilian Army (BRASIL, 1994).

Several and diverse products, systems, and supplies are from the interest of the Army. They include, for example, food rations, uniforms and bulletproof vests, which are mass-produced; tactical radios, produced in hundreds of units; radar systems, produced in dozens of units; and missile systems, usually produced in a few units. Several of these products result from the integration of various critical and highly complex technologies, have custom subsystems, are produced on a small scale and intended for specific markets (oligopolistic). Therefore, associated research and development (R&D) activities require sophisticated management tools.

The stakeholders of the network formed by SCTIEx belong to several public and private organizations, come from various areas of expertise and have diverse backgrounds, cultures and professional experiences. This is a favorable scenario for misunderstandings about important issues that arise throughout the product life cycle, and not only in its R&D phase. It is worth noting that several products and systems with long life cycles (measured in decades) are the core of the SCTIEx portfolio, and its main stakeholders from various organizations change over time.

To illustrate further the richness of this scenario, we bring the example of strategic plannings to obtain such products through R&D, commercializing the innovation and its operation afterward. This type of planning usually integrates the perspective of researchers, engineers, users, and life-cycle managers. Although they have different understandings on how these products should evolve, these actors contribute to the definition of costs, goals, deadlines, and requirements. Besides, they interact differently and more intensely at each phase of the life cycle. While the researcher is more involved in the stage of exploring generic technologies for various applications, the engineer has a more focused view on integrating technologies and designing, whereas the entrepreneur is interested in the commercialization. At the same time, the user is concerned about the performance, reliability, upgrades, and corrections of any failures while using the product. In this context, life-cycle managers try to optimize resources by synchronizing and aligning the efforts spent in these phases.

The literature on Complex Products and Systems (CoPS) addresses the issue of knowledge diversity that need to be integrated and the actors that need to be involved in the process, recognizing the complexity and uncertainties generated in the planning, coordination, and development of CoPS (DAVIES et al., 2011; HOBDAY, 1998). In this context, the importance of achieving common understanding between these actors (GRANT, 1996b; SCHMICKL; KIESER, 2008)and establishing efficient communication is highlighted (AXELSON, 2008).

To achieve common understanding, stakeholders interact through personal mechanisms, such as workshops and meetings, and impersonal mechanisms, such as policies, rules or norms, (GRANT, 1996b). The technology readiness level (TRL) scale can be considered an impersonal mechanism of interaction, as it normalizes communication between different actors, establishes a common language, standardizes critical milestones, and measures the capacity of technological advancement throughout the innovation process (MANKINS, 2009).

Studies that explore impersonal mechanisms in knowledge integration and communication activities, particularly about the TRL tool in the CoPS context, are scant. These studies become even uncommon when the focal element of the analyzed network is a public organization that acts as a contractor, R&D executor and user of the innovation generated in the network, which therefore needs to manage the entire product life cycle or system. Therefore, aiming to fill this gap, this article seeks to investigate the management of Military Systems (MS) from the technology readiness perspective. To this end, this exploratory study investigates the literature on the TRL tool and analyzes the DCT under the issue of knowledge communication and in the context of Complex Product and Systems, considering that, generally, an MS is an example of CoPS. Next, a new research field is proposed, which can contribute to several open questions regarding MS and CoPS management.

The literature review shows the use of the TRL scale in contexts that are different from the ones when it was originally proposed, being broadly employed in the management of CoPS, as in the preparation and monitoring of strategic planning. Additionally, with the analysis of diagnostic documents and management plans of organizations belonging to the DCT, it can be inferred that the adoption of a technological readiness assessment scale could meet the CoPS management needs of DCT, contributing not only to knowledge communication but also with R&D strategic planning at decision-making levels (UNITED STATES, 2009). However, the original TRL scale cannot meet such needs, being able to only contribute to the solution of problems arising from very specific situations. In this context, due to the importance of the theme for the large community of actors involved in the CoPS life cycle, this article presents new research questions and opening new avenues for future studies.

The article has the following organization. Section 2 presents a literature review on knowledge integration and the search for common understanding in the context of CoPS management. Section 3 is devoted to a literature review of the TRL's role in CoPS management. Section 4 presents the research methodology. The details and importance of the representative case are presented in Section 5. Proposals for future studies on CoPS management based on technology readiness are discussed in Section 6. Finally, the conclusions of the article are presented.

2 Achieving common understanding in networks of diversified actors

Knowledge communication problems have been widely discussed in the organizational theory literature in different contexts, focusing, directly or indirectly, on mechanisms that increase common understanding. Regarding R&D activities, the topic addresses causes and effects of inefficient communication and their impacts on common understanding between decision-makers and experts (EPPLER, 2007). According to

Russo e Schoemaker (1990), inefficient communication contributes to several improper decisions made by managers and policymakers. Rambow (2000) discusses the "illusion of terminology", indicating that specialists often overemphasize the importance of technical terms and become frustrated in realizing that people with different backgrounds have difficulty in understanding terminologies, and therefore do not process the knowledge communicated. In this context, Cantoni e Piccini (2004) discuss the "projectionism", a concept in which the expert, when presenting his/her results to decision makers, does not customize his/her analysis to the target audience.

"Common understanding" is essential in the implementation of R&D projects of CoPS, especially those dealing with different organizational cultures and knowledge domains (DAVIES et al., 2011; FRANÇA JUNIOR, 2018). CoPS are defined as capital goods, systems, networks, control units, software packages, specific construction, and services, which are expensive and of sophisticated technology (HOBDAY, 2000). They are distinguished by being integrated by custom components and subsystems; manufactured in units or small batches; designed for specific customer markets with pre-defined requirements; and are eventually governed by political and strategic decisions rather than technical ones (HOBDAY, 1998). These characteristics create many uncertainties in R&D undertakings, especially in the early stages, particularly when there is a reduced level of common knowledge (GRANT, 1996a; SCHMICKL; KIESER, 2008) and common understanding among participants (AXELSON, 2008; OKHUYSEN; BECHKY, 2009) in collaborative programs or projects.

Axelson (2008, p. 11) addresses the issue of common understanding in R&D management as follows:

> [...] it occurred to me that understanding one another's product technology and product development knowledge is one major challenge facing companies in product development collaborations. For example, several managers I met expressed frustration over not being able to make the partner understand e.g. their points of views regarding how to conduct product tests, how to evaluate product quality and how to organise documentation routines. It was often difficult e.g. to understand one another's product design ideas, system interface specifications and component material preferences. [...] Consequently, it was a major issue to company managers how to enable knowledge communication [...].

To achieve common understanding, research on organizational theory suggests that companies relocate people; form coordination groups; create specific roles; and establish organizational interfaces or integration mechanisms (GALBRAITH, 1973; GUPTA; GOVINDARAJAN, 2000; INKPEN, 1996; MAIDIQUE; HAYES, 1984).

In particular, integration mechanisms provide conditions for efficient coordination and for people from different organizations to interact and optimize knowledge communication (SICOTTE; LANGLEY, 2000; SINGH, 2008; TUSHMAN; KATZ, 1980). They are usually framed in two distinct groups: personal and impersonal mechanisms (GRANT, 1996b). Personal mechanisms are those that require intense communication and interaction between the parties, such as visits to partner's organizations, periodic meetings, exchange of employees, job rotation, and so on. On the other hand, impersonal mechanisms are represented by norms, rules, and routines.

Knowledge communication, therefore, refers to the integration mechanisms that organizations use to share, transfer and integrate knowledge (AXELSON, 2008). The literature argues that integration mechanisms create conditions for an improved knowledge communication between different organizations. However, little attention has been devoted to the problem of knowledge communication within networks of very diverse actors, such as those developing CoPS. Also, this literature discusses the issue by highlighting especially the role of personal mechanisms, as they are considered the main mechanisms of integration of tacit knowledge (SRIKANTH; PURANAM, 2011). Impersonal mechanisms have been little explored in the literature, probably due to their supposed ineffectiveness in integrating tacit knowledge (GRANT, 1996b), and not providing the necessary flexibility for organizations, subjected to constantly changing environments, to reinvent and innovate.

3 Technological maturation by readiness levels

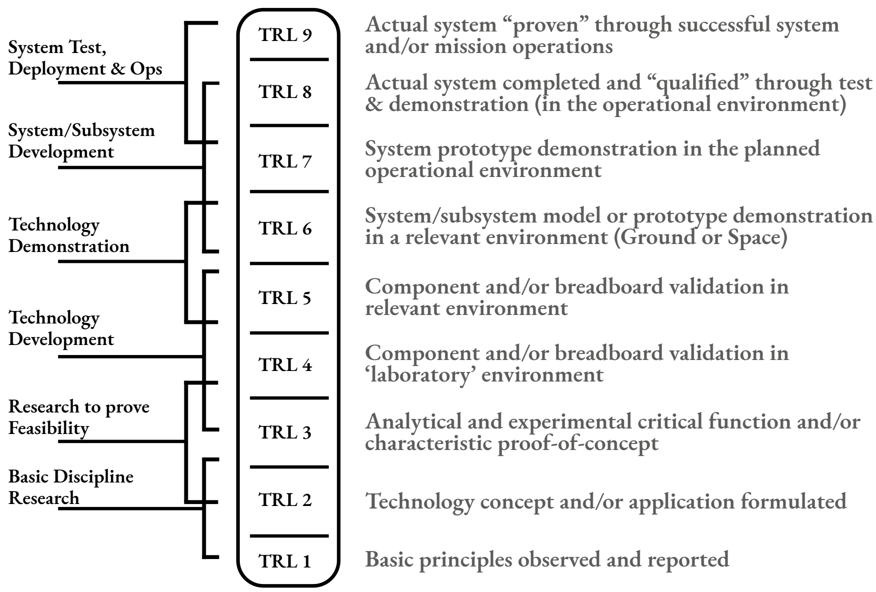
To manage CoPS, simple and traditional project management methods, tools, and techniques can be inadequate and inefficient (DAVIES et al., 2011). The high risks, unpredictability, uncertainties, and communication problems of complex system projects require more sophisticated approaches and long-term planning, with intermediate control points, and integration mechanisms. In this context, it is recommended to employ personal and impersonal communication mechanisms (GRANT, 1996b) to break the design in phases (DAVIES; BRADY, 2016), and to use the concept of prototyping, widely used to reduce development risks (SCHMICKL; KIESER, 2008; STEEN; BUIJS; WILLIAMS, 2014).

Prototyping favors the rapid development of components, subsystems or systems, aiming at anticipating or predicting design problems and solving them at intermediate stages of development. It is, therefore, a process that allows interactions between specialists, with a focus on component interfaces (SCHMICKL; KIESER, 2008; STEEN; BUIJS; WILLIAMS, 2014). These intermediate versions of a system accelerate development, reduce uncertainties, and shorten the learning curve (ELVERUM; WELO, 2015). According to these authors, prototypes are essential for project teams to absorb the tacit knowledge of their partners, to understand better the problem, and communicate not only with each other but also with key stakeholders.

To standardize the long prototyping process adopted in the development of spacial systems, in mid-1970s, NASA developed the TRL scale to provide a measure of the state of new technologies relative to its readiness for operation. This scale is organized into 9 readiness levels, as shown in Figure 1.

In national innovation systems (LUNDVALL, 2007), such as the Swedish, the TRL scale has been serving as a common framework of technology maturation assessment aiming to implement mechanisms of innovation (FRANÇA JUNIOR; LAKEMOND; HOLMBERG, 2017). In a study of the Swedish aerospace system, França Junior, Lakemond, and Holmberg (2017) observed that companies, universities, research institutes, and other organizations use the TRL scale to plan strategies for aerospace technology development, such as the creation of a national innovation agenda (INNOVAIR, 2016). In this context, stakeholders jointly develop research agendas to define roadmaps and prioritize technologies to be developed in collaboration and according to the different TRL levels.

Figure 1 - Technological readiness scale



Source: Mankins (2009).

Other organizations adapt or modify the original TRL scale to their organizational processes and meet their specific needs (JEAN; LE MASSON; WEIL, 2015). For example, the U.S. Department of Defense (DoD) uses a customized nine-level scale for hardware, a second for software, and a third for biomedical technologies (UNITED STATES, 2009). The U.S. Department of Energy (DoE) uses a slightly different scale from the original (UNITED STATES, 2008), particularly at level 9. While NASA requires for TRL 9 an "actual system 'flight proven' through successful mission operations", criteria that can be met with only one mission, DoE specifies for this level an "actual system operated over the full range of expected conditions", which usually requires more than one mission. The customization of the original TRL scale is explored by Straub (2015), who suggests the inclusion of the tenth level (TRL 10), for the context of space systems development. At this level, investments are made to correct faults and bugs identified during continued use, not only after a single use as prescribed in TRL 9.

In Brazil, important government agencies also use the original TRL scale to reduce the risks and uncertainties of R&D projects, but particularizing how levels are assessed, such as the *Agência Espacial Brasileira* – AEB (Brazilian Space Agency) (AGÊNCIA ESPACIAL BRASILEIRA, 2018) and the *Departamento de Ciência e Tecnologia Aeroespacial* - DCTA (Department of Aerospace Science and Technology). In the latter case, a TRL level calculator based on Nolte, Kennedy e Dziegiel (2003) was developed to meet specificities of the Brazilian Air Force (ROCHA; MELO; RIBEIRO, 2017).

Moreover, it is worth mentioning other technological readiness scales that were derived or inspired by TRL. Important scales in this context are the Manufacturing Readiness Level (MRL) scale, the Integration Readiness Level (IRL) scale, and the System Readiness Level (IRL) scale.

The MRL scale was developed by DoD to measure a system's manufacturing maturity. Besides evaluating aspects related to R&D (UNITED STATES, 2016), the scale has the primary objective of inferring about the reproducibility quality of mass-produced products.

Concerned about the insertion of new technologies into existing products, the U.K. Ministry of Defense developed, based on the TRL, the IRL scale (SAUSER et al., 2010). This scale, also graded in nine levels, aims to measure the risk of integrating technology by analyzing the characteristics of its interfaces.

However, it was found that these scales did not fully meet the objective of assessing the technological readiness of complete systems composed of various technologies. The SRL scale was then created to fill this gap (SAUSER et al., 2008).

In summary, different organizations have been using the concept of technology readiness levels and adapting them to their specific needs, suggesting that the original TRL scale does not fully meet CoPS development needs. Moreover, the TRL tool and its variations can be considered impersonal mechanisms of interaction, as they normalize a standardized language structure identifying critical milestones of the technological maturation process (SAUSER et al., 2010). Therefore, the use of these tools improves knowledge communication in a complex network aiming at developing collaborative R&D designs (SAUSER et al., 2010).

4 Methodology

From an exploratory approach, this paper investigates the role of TRL scale when diversified actors search for common understanding in the management of Military Systems. Exploratory studies are appropriate when little is known about the reality in question and a pathway for further research is sought (YIN, 1994).

4.1 Research Design

To achieve the proposed objective, the Science and Technology Innovation System of the Brazilian Army (SCTIEx) is analyzed from the perspective of its focal organization, the DCT, using primary and secondary documentation on its strategic management processes.

4.2 Data collection

This study considers bibliographic and empirical data. Bibliographic data were obtained from a literature review on the personal and impersonal integration mechanisms that contribute to knowledge communication during CoPS's R&D, particularly with the use of the TRL tool. This review covers scientific articles, theses, dissertations, and strategic planning models from other international organizations similar to SCTIEx, such as DoD. The empirical data refer to SCTIEx and were obtained from documentary investigations on government reports, ministerial ordinances, regulatory instructions, management plans, and strategic agendas. Specific documents are the Army's Strategic Plan 2016-2019; Guidelines for Management Restructuring 2015; Guidelines for Transition to DCT Restructuring 2015; the Strategic Plan of ST&I 2016-2019; and the Strategic Diagnosis and Planning of SCTEx 2010[1].

These documents contain information on the short, medium and long term strategies of the military organizations directly subordinate to DCT, such as the *Instituto Militar de Engenharia* – IME (Military Institute of Engineering), the *Centro Tecnológico do Exército* – CTEx (Army Technology Center), and the *Centro de Avaliações do Exército* – CAEx (Center of Army Evaluations), as well as diagnostics addressing their internal (strengths and weaknesses) and external (threats and opportunities) environments. To carry out these investigations in these documents, all the Commanders, Chiefs and Directors of these organizations were interviewed, as well as the Executive Manager of the *Programa Polo de Ciência e Tecnologia do Exército em Guaratiba* - PCTEG (Army Science and Technology Complex Program in Guaratiba), and, as guests, the Presidents of the *Fundação de Apoio a Pesquisa, Desenvolvimento e Inovação – Exército Brasileiro* - FAPEB (Research, Development and Innovation Foundation – Brazilian Army), the *Fundação Ricardo Franco* – FRF (Ricardo Franco Foundation) and the Supervisor of the *Fábrica de Material de Comunicações e Eletrônica* - FMCE (Communication and Electronics Material Factory) of *Indústria de Material Bélico* - IMBEL (Military Material Industry).

4.3 Data analysis

Data analysis was held according to an abductive approach using the matching process suggested by Dubois e Gadde (2002), consisting of systematic comparisons between empirical observations and the theoretical framework. Therefore, this study aimed to match problems identified in diagnoses with theoretical issues related to knowledge communication in CoPS's R&D with the use of the TRL tool. After a continuous and iterative process of bibliographic review and data analysis, the TRL tool became the focus of the study as an impersonal integration mechanism, since its functions match with the SCTIEx's needs of improving their management processes.

In addition, the authors participated in some important R&D projects of the DCT that were at various stages of progress. Therefore, the authors' experience and the iterative process between bibliographic investigation and data analysis increased the internal validity and reliability of the exploratory study (RIEGE, 2003). Additionally, to verify the external validity of the study (RIEGE, 2003), this paper aimed to capture the perspective of three key managers of DCT through informal interviews and feedbacks of this research.

Therefore, this paper presents an overview of the TRL's characteristics, an integration mechanism that enables knowledge communication, together with the strategic aspirations of SCTIEx, a network that is an undergoing transformation process to adapt to the new knowledge era and boost technological innovation. Moreover, it was evaluated the possibilities of using the TRL tool, according to SCTIEx's needs.

1 Plano Estratégico do Exército 2016-2019; Diretriz para Reestruturação da Chefia do DCT 2015; Diretriz de Transição para a Reestruturação do DCT 2015; Plano Estratégico de CT&I 2016-2019; Diagnóstico e Planejamento Estratégico do SCTEx 2010.

5 The science and technology innovation system of the brazilian army (SCTIEx)

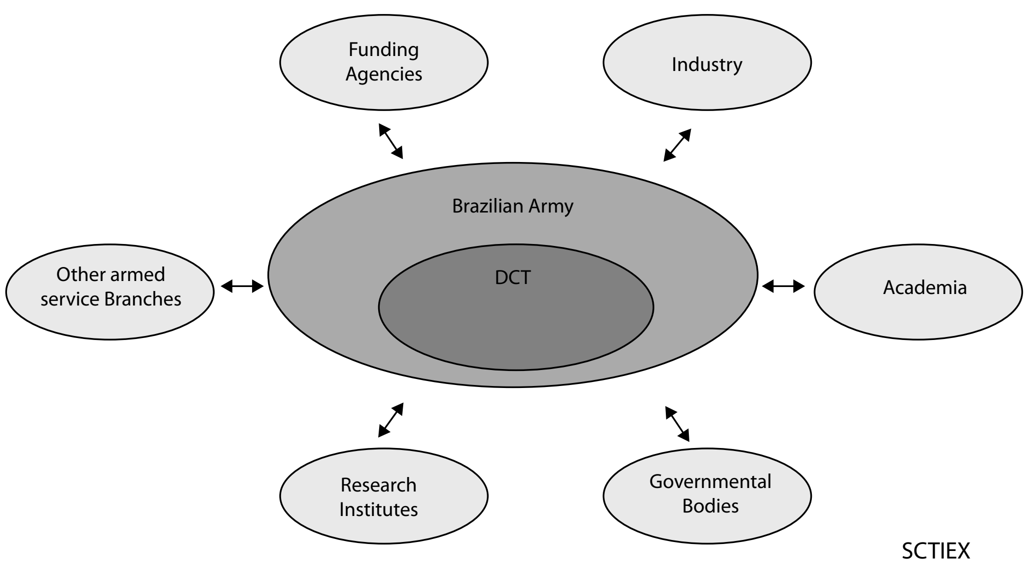
The Brazilian defense sector is fragmented, disjointed, and has low interaction among its actors (CUNHA; AMARANTE, 2011). In addition, this sector interacts with, depends on, and is conditioned by Brazil's National Innovation System, which in turn has been quite inefficient in converting innovation investments into concrete results (GALDINO, 2018). To change this situation, this sector has been undergoing a profound transformation to create an organizational culture that promotes a suitable environment for innovation (FRANCO AZEVEDO, 2018). In this regard, SCTIEx, a key component of the defense industry, actively participates in this transformation process.

5.1 The transformation process

The Science and Technology Innovation System of the Brazilian Army (SCTIEx) "is designed to plan, guide, coordinate, control and execute scientific and technological activities related to Military Systems (MS) and their influences in the areas of the Ground Military Doctrine, Logistics and Personnel" (BRASIL, 1994, our translation). Throughout time, this system has been transforming by adapting to changing national and international scenarios (PRADO FILHO, 2014).

Figure 2 illustrates the current structure of SCTIEx, consisting of military and civil, public and private organizations that interact to promote Science, Technology and Innovation to the Army and the Country.

Figure 2 - Army Science, Technology, and Innovation System



Source: adapted from Brasil (2012).

The relevance of SCTIEx to knowledge communication is due to the following reasons. First, most studies on this subject consider companies to be the focal element and the primary means of coordinating the network. Therefore, choosing a government agency with a similar role of coordinating and directing technological development may bring additional knowledge to the literature, given the State's prominence in taking risks in the maturation of cutting-edge technologies in the early stages of innovation. These risks are hardly assumed by companies, which take advantage of the state-sponsored overflows of these technologies to develop their products (MAZZUCATO, 2014).

Second, DCT is the central element of a system that undertakes several strategic projects, moves hundreds of millions of reais, employs thousands of people and creates partnerships with small, medium and large companies from the most diverse branches of activity, and with universities, research institutes and funding agencies. SCTIEx maintains a close relationship with national Science, Technology and Innovation and is a major player in the Defense sector, responsible for potential overflows into other technology areas (LESKE, 2013).

Third, SCTIEx forms a huge and complex network of diverse players whose R&D projects are long-term, expensive, and have high degrees of uncertainty and technological risk. These characteristics are typical of Complex Product Systems (CoPS) projects (HOBDAY, 1998) that need to integrate a wide range of knowledge that is hardly available in a single organization. Therefore, the complex nature of the SCTIEx network highlights the importance of the common understanding issue.

To support the ongoing transformation process of SCTIEx, DCT conducted diagnoses in its organizations related to teaching, research, development, and innovation – such as IME, CTEx, and CAEx – covering key opportunities of improvement and outlining strategies that are related to the interaction of these organizations with the external environment and thus indicating the need for development and adoption of integration mechanisms.

IME is the Military Organization responsible for training the military engineers, teaching engineering (graduate and pos-graduate programs) and conducting basic and applied research, particularly for SCTIEx projects. From the diagnosis made by IME, it was found that there is little integration with CTEx and the industry. As a result, according to Guidelines EB80-D-07.006 (Project Implementation of the New Military Engineering Institute)[2], IME needs to restructure the graduate programs so that its researchers are increasingly engaged in R&D projects, boosting the system innovation capacity. In addition, it was identified the need to promote greater integration with companies and other organizations by using management models that create a common vision, communicate the vision, and attracts employees aligned with that vision.

CTEx conducts applied scientific research, experimental development, scientific and technological assistance, and knowledge application to obtain MS for the Army. This can be achieved with the support of companies, through new R&D contracts; with the scientific community; or in partnership with companies, ICT and universities altogether. CTEx participates in important Army's projects, including: AV-TM 300 Tactical Missile; OLHAR VDN Military Monocular; Light Preload Mortar 60 mm; Surface-Surface Missile 1.2 AC (MSS 1.2 AC); SABER M200 Radar; SABER M60 Radar; Software-defined Radio (SDR); Automated Machine Gun Repair X (REMAX); Esquilo and Fennec Helicopter Simulator (SHEFE); and Light General Purpose 4×4 Vehicle (VLEGA)[3].

2 Implantação do Projeto do Novo Instituto Militar de Engenharia.

3 Reparo de Metralhadora automatizada X (REMAX); Simulador de Helicópteros Esquilo and Fennec (SHEFE); Viatura Leve de Emprego Geral Aerotransportável (VLEGA GAÚCHO).

The CTEx's diagnosis reported: low integration with universities and other research centers; few national companies trained and interested in developing MS; insufficient financial resources offered by funding agencies; heterogeneous and unequal distribution of financial resources; dispersed efforts from stakeholder to achieve common objectives; lack of formal tools, systems and practices that contribute to decision-making processes; low standardization of risk analysis processes; low maturity of process and project management; and poor performance indicators.

As a result, CTEx defined that it needs to increase integration with the scientific community (IME included) and with companies; master critical technologies that ensure strategic and operational advantages to the Army; improve R&D management of projects; and organize information and knowledge management with a compatible Information Technology infrastructure.

The primary mission of CAEx is to evaluate prototypes and pilot batches of MS, products from the National Defense Industrial Base (BID), or purchased from other nations, and Army Controlled Products (PCE)[4], as well as to develop studies on metrology. In its strategic diagnosis, it was indicated the low maturity of documented and widespread rules of MS evaluation processes and the possibility of fostering the defense industry through R&D collaborations, taking advantage of the success of the existent PCE evaluation process and the established relationship with companies.

Therefore, in its diagnosis, DCT demands several strategic initiatives that essentially highlight the need to develop methodologies, tools, and procedures to:

- Measure innovation;
- Develop technological roadmaps;
- Support the R&D strategic planning of the military organizations; and
- Strengthen the integration of SCTIEx stakeholders into a Triple Helix model of innovation.

5.2 The SCTIEx characteristics

To operationalize the strategic initiatives demanded by DCT, it is necessary in-depth studies and sophisticated management models that need to be proposed, tested and validated. These studies and models should take into account the listed attributes that characterize SCTIEx and similar networks, as well as take advantage of the current knowledge available in the specialized literature. Next, two attributes from SCTIEx are highlighted.

First, the TRL scale covers only part of the life cycle of complex systems (SAUSER et al., 2008). When analyzing the life cycle of military systems, six phases are identified (Lima, 2007) (Chart 1).

Chart 1 - Life Cycle of Brazilian Army Materials

1st Phase	2nd Phase	3rd Phase	4th Phase	5th Phase	6th Phase
Survey of Needs and Conceptual Formulation	Planning and Scheduling	Research and Development (R&D)	Production or Acquisition	Use	Disposal

Source: Lima (2007).

4 Base Industrial de Defesa (BID); Produtos Controlados pelo Exército (PCE).

In the 1st phase, the needs are identified, the strategies and priorities are defined, and the operational and technical requirements are elaborated. In the 2nd phase, the Army senior management decides whether the material should be purchased on the market (national or international) or developed by SCTIEx through R&D. Once decided, an acquisition or development project is included in the Army's strategic planning. In the 3rd phase, if the decision of obtention involves R&D, the following sub-phases take place: R&D of the system and prototype generation; prototype evaluation; production of a pilot batch; evaluation of the pilot batch. In the 4th phase, the product is acquired, received, stocked, and distributed. In the 5th phase the use and detection of deficiencies, failures and opportunities for improvement are held, generating the possibility of incremental innovations, as well as data collection that will support the R&D of new product generations, with the possibility of more innovations. Over time, the information collected will be able to support modernization, improvement and disposal decisions. In the 6th and last phase, the material is deactivated, removed from its inventory, and disposed.

Throughout these six phases, the utilization of the original TRL scale would cover only part of the third phase, i.e. the R&D phase. However, the other phases of the life cycle are equally important. For example, for many military systems, the cost of use (5th phase) is around 70% of the total life cycle cost, whereas the development cost is around 20%, as (SAÚDE, 2010) shown in Chart 2.

Chart 2 - Percentage distribution of life cycle costs of some equipment

System	R&D costs	Acquisition costs	Operation and maintenance costs
Airplanes	20%	18%	62%
Warships	2%	23%	75%
Missiles	52%	30%	18%

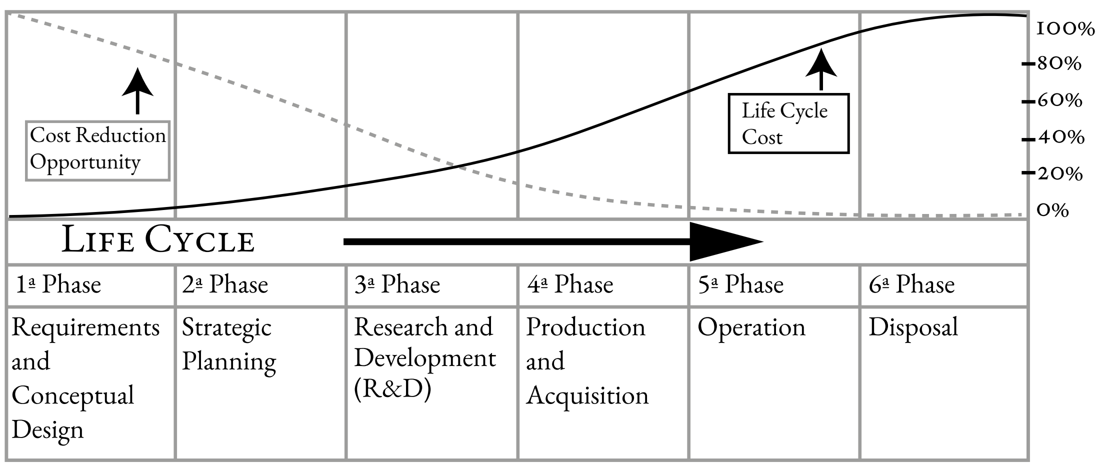
Source: Paulo (2006).

Besides, as discussed by Barringer e Weber (1996), the first two phases present the greatest cost reduction opportunities (Figure 3), highlighting the importance of an efficient management of the life cycle phases.

The limitations of the original TRL scale were described in Section 3. Several organizations use different TRL-based readiness scales to meet their needs, such as the MRL, SRL, and IRL scales, and even the modified TRL scale with additional levels. Although these variations increase the scope of the concept of technological readiness, there are still important gaps regarding its use in complex networks such as the SCTIEx.

For example, the original scale does not consider the production and evaluation of the pilot batch of the 3rd phase. Despite the fact that the MRL scale involves these activities, it does not consider the particularities of the Brazilian Defense Industrial Base, as it does not assess the risks and obstacles created with critical components purchased from other nations, and the uncertainty of regular financial resources for ongoing R&D projects and of government procurement. These aspects impact negatively on R&D capabilities and MS manufacturing activities. Another important phase not covered by technological readiness levels is the 6th. Although Straub (2015) proposes the inclusion of level 10^{th} in the TRL scale to address user's operation, there are still many issues to be clarified regarding the need for modernization, improvement, disposal or even reengineering (i.e. to return to initial levels of the TRL scale).

Figure 3 - Cost evolution according to life cycle of materials



Source: Adapted from Barringer and Weber (1996).

Moreover, the military systems acquired by the Army varies largely in terms of complexity. The Army manages the life cycle of complex products such as missiles, tanks, and radars, as well as mass-produced products such as uniforms, assault rifles and bulletproof vests. Between these extremes there are systems sharing common features, such as long-range unmanned aerial vehicles (UAV), which are costly and intended for specific customer markets but can also be mass-produced and integrated largely by commercial off-the-shelf products (HAMBLING, 2015). This variety of systems and products is addressed in the CoPS literature in terms of degrees of complexity (HOBDAY, 1998).

Therefore, the TRL scale, originally designed for highly complex space technologies and systems, does not fully meet the needs of networks such as the SCTIEx, as it is not suitable for less complex products and systems that do not need to reach all levels of the scale; nor cover all phases of the MS life cycle that need to be managed by the SCTIEx.

6 Proposal for future studies: management of complex systems based on technological readiness

Proposals for future studies are presented next to fill the gaps identified in the previous section.

6.1 Technology readiness scale customized for complex networks

Despite the benefits of adopting a readiness scale in complex networks such as SCTIEx, the specificities of this type of network cannot be met by scales available in the literature, requiring customizations. However, these customizations should adhere to the original TRL scale, in order to enable knowledge communication with exogenous actors of the network, including other countries. Moreover, it deems necessary a technology readiness scale that covers the key phases of the life cycle of complex products (Figure 3) and takes into account its degrees of complexity. In this context, the following questions need to be answered:

1. What phases of the life cycle should a custom technology readiness scale encompass? And with how many and which levels of readiness?

2. How to frame/audit the maturity of a product or system at each level?

3. How the importance of adopting a technology readiness scale in the product life cycle management is influenced by degree of the product complexity?

6.2 Strategic planning of R&D based on technology readiness

As resources are often limited, focal organizations of a complex network cannot effectively participate in all R&D undertakings. Thus, during early stages of the life cycle (1st and 2nd phases), to prioritize critical technologies and decide on the appropriate form and intensity of involvement in a project, it is important to adopt strategic management models that optimize employment of human and financial resources. For this, managers need accurate information on the readiness levels of universities, companies, research centers in critical areas and technologies.

An analysis based on technological readiness levels may reveal different scenarios with distinct implications for the allocation of human and financial resources, stakeholders' involvement, staff training, chronogram setting, dual technology development, and overall objectives. For example, a technology of interest of the Army that has a national R&D capacity between TRL 3 and TRL 5 indicates a potential for generic technology development, capable of attending more than one application. With technological roadmaps, a common R&D agenda can be developed among actors of the Triple Helix (INNOVAIR, 2016) with the aim of prototyping and advancing the maturity of critical technologies. Therefore, the following research questions are proposed:

1. How to define the criticality of technologies in a national context?

2. How to map national and international organizations that supply critical technologies according to the technological readiness level?

3. How can a technology readiness scale help to design technological roadmaps and common R&D agendas among actors in a complex network?

4. How to include the concept of technology readiness in life cycle management methodology?

6.3 Analysis of technical feasibility and risks of R&D based on technology readiness

For the DoD, a Critical Technology can be defined as a technology belonging to a complex product system, being essential to meet established technical and operational requirements (within acceptable costs and deadlines) which use or application is new or has high technological risks during its development (UNITED STATES, 2015). When trying to develop a product whose critical technologies indicate low TRL, the assumption is that there is a great risk that R&D obstacles and chall enges increase. This causes inaccuracies in budgeting and chronogram estimations, increasing chances of higher development costs and schedule delays (UNITED STATES, 2015), which in turn makes stakeholders insecure and frustrated.

In a study held in 62 R&D programs from DoD, the U.S. Government Accountability Office (GAO) found that 33% of these programs began with some immature critical technologies (Below TRL 7). These programs suffered an average cost increase of 32% and an average delay of 20 months. In contrast, the others experienced a cost increase of only 2.6% and an average delay of 1 month (UNITED STATES, 2015).

Based on these studies, several countries adopt TRL levels 6 or 7 as a critical milestone that indicates the technical feasibility of starting an R&D project aiming at designing a product by integrating various critical technologies. Whereas critical technologies do not reach these levels, the U.S. GAO (UNITED STATES, 2015) recommends that the R&D effort falls on its maturation.

This approach raises the following fundamental question: How to develop a methodology for risk analysis and technical feasibility based on technological readiness for decision-making on:

- purchase the desired system in the international market or perform R&D (in the country or in collaboration)?
- R&D procurement for the entire product design and its integration, or for the maturation of its critical technologies?

6.4 Knowledge communication mechanism

The literature review on the TRL indicated its potential in helping achieve common understanding by identifying R&D stages of technologies that need maturation. With maturation milestones standardized across a complex network of diverse actors, decision-makers and managers can have a broader and fine-grain view of the technological evolution throughout the product life cycle, which facilitates the strategic planning of R&D projects and programs (of integration and maturation of subsystems). In this sense, the prototyping of technologies and its framing into a TRL level encodes the tacit knowledge of the specialists involved.

Therefore, it is implied that the technology readiness tool, an impersonal mechanism, can facilitate the use of personal mechanisms and enable the integration of tacit knowledge, and not only codified knowledge. Thus, it is suggested that, although representing an impersonal mechanism (generally used to integrate codified knowledge) (SRIKANTH; PURANAM, 2011), has attributes of personal mechanisms given its potential to support common understanding and enable the codification of tacit knowledge.

To confront these expectations on the TRL scale, the following questions are raised:

- How can the TRL tool support common understanding among diverse actors in a complex network?

- What is the role of the TRL scale in the codification of tacit knowledge?

7 Conclusion

This paper revealed that the TRL scale covers only part of a Military System life cycle. On the other hand, it illustrated how adopting a customized technology readiness scale can increase the efficiency of complex product system management and support decisions that go beyond R&D.

As this topic is not much explored in the literature, this study raised important research questions, analyzing a specific case, the SCTIEx. The answers can bring large benefits not only to the aforementioned network, raising the level of management of Science, Technology and Innovation within the Brazilian Army, but also to society as a whole, given the technological spillover effects that the defense sector is capable of generating, contributing to economic growth and national development. Given that SCTIEx has similarities to other networks that deal with complex products, further studies aiming at investigating the questions under discussion may contribute not only with the diverse community of experts working with military systems but also with CoPS literature.

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