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"COUPLED PROCESSES" AS DYNAMIC CAPABILITIES IN SYSTEMS INTEGRATION

"Processos acoplados" como capacidades dinâmicas na integração de sistemas

"Procesos asociados" como capacidades dinámicas en la integración de sistemas

ABSTRACT

The dynamics of innovation in complex systems industries is becoming an independent research stream. Apart from conventional uncertainties related to commerce and technology, complex-system industries must cope with systemic uncertainty. This paper's objective is to analyze evolving technological paths from one product generation to the next through two case studies in the Brazilian aerospace industry, considering systems integration as an empirical instantiation of dynamic capabilities. A proposed "coupled processes" model intertwines two organizational processes regarded as two levels of dynamic capabilities: new product and technological developments. The model addresses the role of emergent properties in shaping a firm's technological base. Moreover, it uses a technology readiness level to unveil systems integration business tricks and as a decision-making yardstick. The "coupled processes" model is revealed as a set of dynamic capabilities presenting ambidexterity in complex systems industries, a finding that may be relevant for newly industrialized economies.

KEYWORDS | Systems integration, dynamic capabilities, ambidexterity, industry value stream, technology readiness level.

RESUMO

A dinâmica de inovação em indústrias de sistemas complexos está se tornando uma linha de pesquisas independente. Além das incertezas convencionais relacionadas ao comércio e à tecnologia, as indústrias de sistemas complexos precisam lidar com uma incerteza sistêmica. O objetivo deste artigo é analisar os caminhos tecnológicos em evolução, de uma geração de produto para a seguinte, através de dois estudos de caso na indústria aeroespacial brasileira, considerando a integração de sistemas como uma exemplificação empírica das capacidades dinâmicas. Um modelo proposto de "processos acoplados" entrelaça dois processos organizacionais considerados como dois níveis de capacidades dinâmicas: desenvolvimento de novo produto e desenvolvimento tecnológico. O modelo trata do papel de propriedades emergentes na formação da base tecnológica de uma empresa. Além disso, ele utiliza níveis de maturidade tecnológica para revelar truques de negócios na integração de sistemas, e também como parâmetro para tomada de decisões. O modelo de "processos acoplados" revela-se como conjunto de capacidades dinâmicas que apresentam ambidestria em indústrias de sistemas complexos, um resultado que pode ser relevante para economias recém-industrializadas.

PALAVRAS-CHAVE | *Integração de sistemas, capacidades dinâmicas, ambidestria, fluxo de valor de indústria, nível de maturidade tecnológica.*

RESUMEN

La dinámica de la innovación en industrias de sistemas complejos se está convirtiendo en una línea de investigación independiente. Aparte de las incertidumbres convencionales relacionadas con el comercio y la tecnología, las industrias de sistemas complejos deben lidiar con la incertidumbre sistemática. El objetivo de este artículo es analizar los caminos tecnológicos cambiantes de una generación de productos a la próxima, a través del estudio de dos casos en la industria aeroespacial brasileña, considerando la integración de sistemas como una instanciación empírica de capacidades dinámicas. Un modelo propuesto de "procesos asociados" interrelaciona dos procesos organizacionales considerados como dos niveles de capacidades dinámicas: desarrolo de nuevo producto y desarrolo tecnológico. El modelo trata el papel de propiedades emergentes en darle forma a la base tecnológica de una firma. Además, usa niveles de preparación tecnológica para desvendar trucos empresariales de integración de sistemas y como criterio de toma de decisiones. El modelo de "procesos asociados" se revela como un conjunto de capacidades dinámicas que presenta ambidexteridad en industrias de sistemas complejos, un descubrimiento que puede ser relevante para economías recientemente industrializadas.

PALABRAS CLAVE | *Integración de sistemas, capacidades dinámicas, ambidexteridad, flujo de valor de la industria, nivel de preparación tecnológica.*

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INTRODUCTION

The dynamic capabilities approach enables an understanding of the different paths that firms use to compete and the importance of history in shaping these paths. The approach follows the resource-based view (RBV) of the firm (Helfat et al., 2007), as originally proposed by Penrose (1959) and extended by Wernerfelt (1984) in terms of its modern conception.

As proposed by Hobday (1998, 2000), the dynamics of innovation for complex products and systems (CoPS) present a sharp distinction in many dimensions when compared with mass-produced goods. The variability of each unit of production is very high. Moreover, the configuration of an engineering-intensive product responds to specific customers' demand. Transactions follow a business-to-business pattern, a process that is characteristic of high-cost capital goods. Another distinction is that CoPS industries are marked by the absence of a dominant design in the sense proposed by Abernathy and Utterback (1978) and Utterback (1994).

The coordination mechanism of CoPS industries, which merges attributes of hierarchies and markets, is systems integration (Brusoni, Prencipe, & Pavitt, 2001; Pavitt, 2003). We explore systems integration as an empirical instantiation of dynamic capabilities (Hobday, Davies, & Prencipe, 2005) that enable the coordination of complementary assets of interorganizational innovation networks, thereby stressing the role of the systems integrator (Brusoni et al., 2001; Eisner, 2008; Prencipe, Davies, & Hobday, 2003). We consider the view that dynamic capabilities are embedded in project-based organizational processes that are pervasive in interorganizational innovation networks. We undertake this investigation by analyzing the depth and width of systems integrators' technological knowledge.

We use a comparative analysis of two cases that we study in-depth. Our analysis considers the passage from one generation to the next of a platform product in order to define precisely the timeframe and granularity of organizational change (Helfat & Winter, 2011). Both cases are from the Brazilian aerospace industry. The first considers the aeronautical sector and Embraer, a Brazilian aerospace firm. In this regard, the first case examines Embraer's platform of E-Jets from the first generation (EMBRAER E170-190) to the second generation (EMBRAER E170-190 E2). The second case considers the space sector and the role of Brazil's National Institute for Space Research (Instituto Nacional de Pesquisas Espaciais [INPE]) as a systems integrator in the China–Brazil Earth Resources Satellite (CBERS) platform, from the first generation (CBERS 1 and 2) to the second-generation (CBERS 3 and 4) platforms.

Besides commercial and technological uncertainty (Keynes, 2004; Teece, Peteraf, & Leih, 2016), systems integrators have to cope with systemic uncertainty (Rosenberg, 1982) that stems from emergent properties (Rechtin, 2000; Sillitto, 2005; Zandi, 2000). In this regard, the "coupled processes" model intertwines first-order and second-order capabilities: new product development and technological development. The model considers a systems integrator's technological base, which is composed of technologies in the proprietary and integration domains. It also considers that an organization can present ambidexterity (O'Reilly & Tushman, 2008). The model was developed by following the engaged scholarship method (Ven & Johnson, 2006), an approach that was used to analyze the evolving technological paths in both case studies, taking account of systems integration as an instantiation of dynamic capabilities (Davies & Hobday, 2005).

Complementarily to Hobday et al. (2005), we argue herein that the upstream movement in the industry value stream, from the first to the second generation of the two platforms of products, is a specific feature of systems integration that is characteristic of newly industrializing economies (NIEs). This current multiple case study contributes to the literature by providing an empirical advance in dynamic capabilities research, identifying the "coupled processes" model as a set of dynamic capabilities that present ambidexterity in CoPS industries. Such research may be relevant for NIEs.

SYSTEMS INTEGRATION AS A DYNAMIC CAPABILITY

Systems integration has been evolving as a strategic capability of modern corporations since its early years in the 1940s and 1950s in the military industry (Sapolsky, 2003). Nowadays, systems integration has been adopted as a competitive strategy in many different industries and is an empirical instantiation of dynamic capabilities (Hobday et al., 2005). Such adoption is especially evident in CoPS industries, which, as defined by Hobday (1998), are high cost, engineer-intensive, and highly customized, and use capital goods. CoPS industries represent the backbone of all economic systems (Rosenberg, 1976). In CoPS industries, it is possible to identify three levels of systems integration: subsystems, systems, and systems of systems (Gholz, 2003). At all three levels, a firm must be able to define systems architecture properly, divide work through interorganizational innovation networks, and take responsible for final integration (Chagas & Campanario, 2014).

Henderson and Clark (1990) were the first to conceptualize and stress the importance of architectural knowledge for systems integration and its implications for organizational processes and the formation of organizational learning bias. Teece, Pisano, and Shuen (1997) explored how the stock of architectural knowledge defines a firm's technological opportunities through the concept of path dependence and stresses the role of the coordination of complementary assets in value-creation capabilities. From the economic standpoint, the importance of controlling assets that are outside the boundary of a firm is central to an industry's organization, as first identified by Richardson (1972). The control over assets that are not owned by a firm, but are important to its value-creating strategies, may be framed as a hybrid coordination mechanism somewhere between markets and hierarchies. Moreover, such control has been stressed as central to the formation of interorganizational innovation networks (Barney, 1991; Prahalad & Hamel, 1990; Teece & Pisano, 1994; Teece et al., 1997).

With regard to industrial coordination, the central concept that distinguishes CoPS industries from mass-production industries is dominant design (Utterback, 1994). The presence or absence of a dominant design has a profound implication for the pattern of competition established in an industry and to the innovation strategy of its players (Hobday, 1998; Tushman & Murmann, 2003). Exhibit 1 presents five main characteristics that distinguish the dynamics of innovation in CoPS industries and mass-production industries.

Exhibit 1. **Main characteristics that distinguish the dynamics of innovation in CoPS**

Characteristics	CoPS/Project organization	Mass production
Products	Capital goods Complex interfaces Hierarchical/systemic	Consumer goods Simple interfaces Simple architectures
Production	Project/small batch	High volume/large Batch
Innovation paths	Craft-based Innovation path defined ex ante	Formalized, codified Innovation path is mediated by the market
Industrial coordination	Multifirm alliances: PBO Long-term stability at the systems integrator level	Single firm as producer Dominant design signals industry shakeout
Competitive strategies	Systems integration capabilities targeted for complex architectures	Volume production capabilities (e.g., lean production, total quality management (TQM))

Source: Adapted from Hobday (1998).

ORGANIZATIONAL PROCESSES OF SYSTEMS INTEGRATION

The concept of dynamic capabilities defined through organizational processes was first proposed by Eisenhardt and Martin (2000). Their definition of dynamic capabilities is as follows: "The firm's processes that use resources—specifically the processes to integrate, reconfigure, gain and release resources—to match and even create market change" (p. 1107).

By this definition, a firm's processes bridge strategic content, namely what resources should do to match or create market change, to strategic processes, namely how to use resources through the firm's processes. From this perspective, the essence of dynamic capabilities is in the organizational processes. Paths and positions stem from such processes. Moreover, the performance and evolutionary fitness of one organization in its industry value stream can be analyzed using its processes and the logic of the RBV (Helfat et al., 2007).

With regard to CoPS industries, systems integration processes consist of a combination of systems engineering and project management (Davis & Hobday, 2005; Eisner, 2008; Prencipe et al., 2003). Both disciplines may be considered as best practices (Eisenhardt & Martin, 2000) that are used to carry out the development and deployment of dynamic capabilities (Helfat et al., 2007). Further, the idiosyncratic character of organizational processes stems from the equifinality principle. In this sense, systems integration is necessary, but not sufficient, for value-creating strategies.

While project-based organizations (Hobday, 2000; Project Management Institute [PMI], 2013) present the appropriate conditions for the development of CoPS industries through the temporary definition of interorganizational networking for innovation, systems engineering provides the design rules (Baldwin & Clark, 2000) that should be applied to the conception, development, and deployment of CoPS. The merging of these two disciplines provides the means to conceive and implement value-creating strategies (Barney, 1986; Wernerfelt, 1984, 1995).

The "twin processes" of vertical integration and disintegration (Hobday et al., 2005) express many of the value-creating strategies for organizations in advanced industrialized economies. We argue herein that the "twin processes" are better understood if one considers the "coupled processes" of new product development and technological development (Cooper, 2007), both of which are important instantiations of dynamic capabilities.

The understanding that dynamic capabilities govern the rate of change of ordinary capabilities (Collis, 1994; Collis & Montgomery, 1998; Winter, 2003) provides the rationale for the proposal of the "coupled processes" model. However, we expand this understanding to CoPS industries for two main reasons.

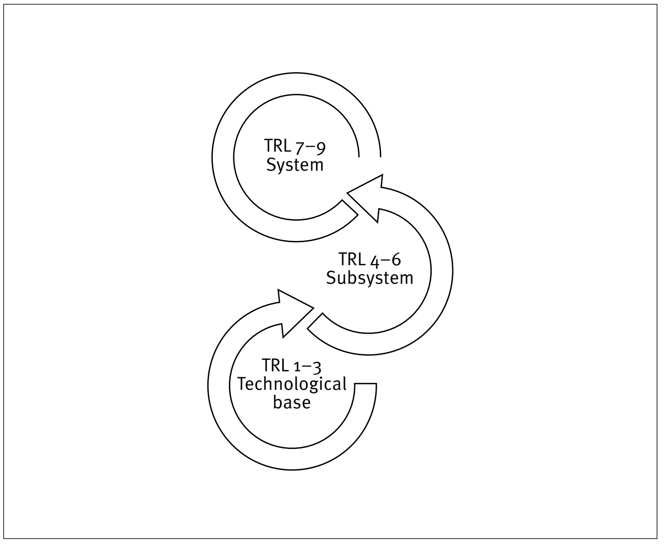
The first is that a CoPS project life cycle starts earlier and finishes later (Sato & Chagas, 2014) than a mainstream project life cycle (PMI, 2013) and what may be considered a prototypal example in the field of mass-produced goods (Baldwin & Clark, 2000). Moreover, because CoPS industries produce highly customized capital goods, which present many possible configurations for each single production unit, a significant overlap exists between first-order capabilities (new product development) and "zero-level" capabilities (Winter, 2003). For the same reason, a significant overlap exists between second-order capabilities (Winter, 2003) and first-order capabilities (Helfat & Winter, 2011). In CoPS industries, the success of a "project-based organization" (PBO) requires ambidextrality as a dynamic capability (O'Reilly & Tushman, 2008).

MEASURING THE KNOWLEDGE DEPTH OF SYSTEMS INTEGRATION

We use the concept of "technology readiness level" (TRL) (Mankins, 2009) to measure the knowledge depth of systems integration and as a decision-making yardstick. TRL was created by the National Aeronautics and Space Administration (NASA) in the 1970s and is now considered an important reference tool. New systems in CoPS industries normally depend on prior advanced technologies that result from research and development (R&D) efforts. The concept of triple constraint considers cost, time, and performance the main variables that must be balanced in project management (Kerzner, 2013). If R&D is not properly carried out to promote the progressive maturity of a new technology, the development of the new system will probably present schedule slippage, cost overruns, and a reduction in performance objectives.

TRL ranges from level one to level nine. The costs involved in passing from one level to the next grow exponentially. The first level represents the basic principle of a potential technology that is observed and reported. The ninth level represents the actual system in the operational environment properly performing its functionalities. The definition of systems architecture establishes the systems hierarchy and the way in which integration should take place. "Without very careful effort at developing an appropriate architecture for a system, there will be little hope of integration" (Sage & Lynch, 1998, p. 176). For a system to work properly, not only must a single technology mature; all technologies incorporated in the subsystems should perform functionalities that are integrated in the system, as illustrated in Figure 1. While the first three levels of TRL may be considered basic and applied sciences of the relevant technology, the last three levels represent the progressive maturity of the entire system. The three levels in the middle represent the maturation of technological elements with different levels of aggregation, from components to the system passing through subsystems and equipment. TRL helps to measure path dependence and the organizational learning process. It explains that technological evolution moves at its own pace and with its own increasing costs. Moreover, it makes explicit that for technological development, "history matters" (Penrose, 1995; Teece et al., 1997).

Figure 1. **Technology readiness level commonly related to systems hierarchy development effort**



According to Teece et al. (1997):

> Thus, a firm's previous investments and its repertoire of routines (its history) constrain its future behavior. This follows because learning tends to be local. That is, opportunities for learning will lie in the neighborhood of what is already familiar, and thus will be transaction and production specific. (pp. 522-523)

TECHNOLOGICAL BASE: PROPRIETARY AND INTEGRATION DOMAINS

We now explore the role of a systems integrator in forming a firm's technological base, considering the concept of dynamic capabilities in CoPS industries in NIEs (Kim & Nelson, 2000). A systems integrator is a firm that establishes and leads a network from organizational and technological standpoints (Brusoni et al., 2001).

According to Penrose (1995), the technological base of an organization refers to the set of knowledge and skills required to perform research, development, production activities, and operational activities related to a specific technological field. The width of a technological base represents the number of scientific and technological disciplines that are necessary to compete in a specific industrial segment. CoPS industries are characterized by an extremely wide technological base; namely, by a large number of scientific and technological disciplines that evolve and, at a given moment, are integrated to define a system that can meet the needs of its stakeholders (Brusoni et al., 2001; Chagas & Campanario, 2014; Prencipe et al., 2003; Rechtin, 2000; Rechtin & Maier, 2010).

From the cost standpoint (Richardson, 1972, 2003), a systems integrator has to coordinate complementary assets (Teece et al., 1997) in order to create its technological base. Besides the capacity to coordinate complementary assets, a necessary condition for the competitiveness of a systems integrator is to master technologies from TRL one to nine as proprietary technologies. We consider these technologies in the proprietary domain because they are part of the core competence (Prahalad & Hamel, 1990) of a systems integrator. We consider integration domain as another category of technologies that a systems integrator should develop, starting from its own R&D efforts that provide the innovative capacity for the whole system. However, detailed design and manufacturing may be considered complementary assets (Teece et al., 1997).

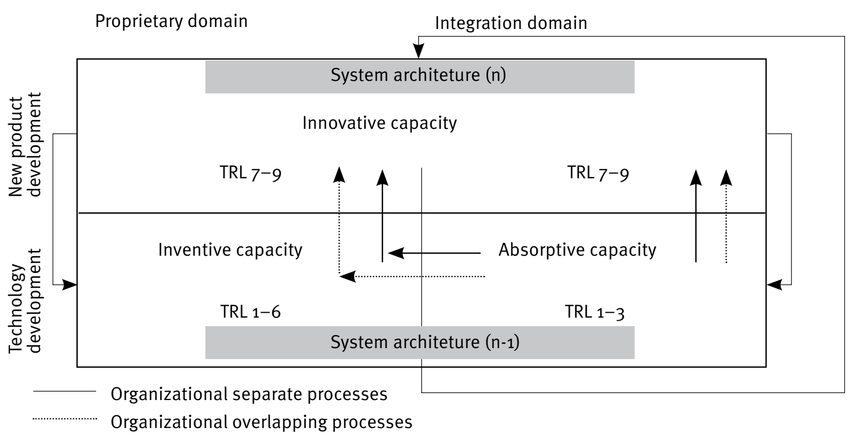
THE "COUPLED PROCESSES" MODEL

Absorptive capacity (Cohen & Levinthal, 1989, 1990) involves the sensing and seizing of technologies (Teece, 2009). We argue that some technologies are in the integration domain. Eventually, these technologies should be reconfigured in order to convert those in the integration domain into technologies in the proprietary domain. This conversion implies the capacity to invent or adapt technologies to the system being developed, or that should be developed, by a systems integrator. We propose the "coupled processes" model because this regards new product development and technological development as organizational processes. We adopt this method in order to frame the flux of knowledge from the integration domain to the proprietary domain, following RBV logic and the dynamic capabilities approach. The changing position of a systems integrator in the industry value stream, from one generation to the next, may be better understood by considering the "coupled processes" that underpin the "twin processes." The width and depth of the stock of knowledge and skills usually vary significantly from organization to organization. Such variations occur in accordance with the pace and direction of the cumulative efforts of R&D and past experience acquired from the collective efforts of the definition, development, and operation of CoPS (Chagas, 2009).

The "coupled processes" model illustrated in Figure 2 presents the stock and flows of knowledge (Dierickx & Cool, 1989), conceived for the technological base of a systems integrator and stressing the organizational learning that emerges from transitional processes (NASA, 2007). Changes in position in an industry value stream, from one generation of a product platform to the next, stem from the understanding of the dynamics of these stock and knowledge flows of knowledge. This logic of bidirectional knowledge flows is essential in the face of emergent properties and is also aligned with the idea of collective learning, as proposed by Penrose (1995):

> Increasing experience shows itself in two ways – changes in knowledge acquired and changes in the ability to use knowledge. There is no sharp distinction between these two forms because to a considerable extent the ability to use old knowledge is dependent on the acquisition of new knowledge. (p. 53)

Figure 2.**"Coupled processes" model**



An organization's separate processes are executed when new product development is preceded by technological development. If both processes occur in parallel, we refer to them as overlapping processes.

RESEARCH METHODOLOGY

Eisenhardt and Graebner (2007) proposed a methodology for developing theories from cases. The methodology starts with recognizing patterns of relationships within and among analyzed cases, which form the main aspect of the methodology.

The steps of the Eisenhardt (1989) methodology include research definition and planning, the selection of cases to be analyzed, formulation of the research instruments, data collection, analysis and comparison within and among cases, hypothesizing, a comparison with the literature, and theoretical saturation, if appropriate.

Because the selected case studies were analyzed very carefully for a long time, and from distinct perspectives (Chagas & Cabral, 2010; Chagas, Cabral, & Campanario, 2011; Chagas & Campanario, 2014), an interesting opportunity was presented to promote engaged scholarship. Ven and Johnson (2006) defined engaged scholarship as collaborative research in which academics and practitioners bring together different perspectives and competencies about a complex problem that is subject to uncertain conditions. Engaged scholarship has important practical relevance and contributes significantly to the advance of theoretical knowledge in a given domain.

We chose a comparative case study approach to pursue the research objective posed in this study; namely, to analyze the evolving technological paths from one product generation to the next through two case studies in the Brazilian aerospace industry, considering systems integration as an instantiation of dynamic capabilities.

Embraer and INPE case studies were based on interviews conducted in 2015–2016 with a system manager of INPE multispectral (MUX) and wide field imager (WFI) cameras at INPE headquarters, and two Embraer technology development managers and a product development engineer at Embraer headquarters. The interviewers were prepared and asked semi-structured questions. They took their own notes during the interviews, conducted qualitative content analysis, and validated the results with the interviewees. A limitation is that the interviews were not allowed to be recorded. The case studies and the research were complemented by previously validated interviews conducted in 2007–2008 with a CBERS Brazilian program manager and a CBERS Brazilian system architecture manager, and in 2005–2009 with an Embraer 190 program manager, an engineering specialization program (PEE) coordinator, a control law simulation engineer, a software integration systems manager, and a technical consultant. The final results were validated at the organizations with the 2015–2016 interviewees. Exhibit 2 presents the results in a comparative table.

Exhibit 2. **A comparative table of data collected during interviews**

Topic	INPE MUX Camera case study	Embraer fly-by-wire case study
From integration to proprietary domain		
Original system approach (integration domain)	CBERS-1 and 2 equipped with Brazilian WFI camera and other Chinese cameras including mid-resolution CCD camera. WFI camera had optics technologies at integration domain.	EMBRAER 170/190 family (1st gen: E1) with FBW control system, developed with a risk partnership (Honeywell).
New system approach (proprietary domain)	CBERS-3 and 4 equipped with Brazilian WFI (2nd gen.) and mid-resolution MUX camera, besides other Chinese cameras. WFI (2nd gen.) and MUX at proprietary domain, being developed and manufactured in Brazil.	EMBRAER 170/190 family (2nd gen: E2) with full FBW, developed by Embraer (software).
Complex product and system development		
Initial technological base	Camera integration and electronic technologies were at a high TRL level, but optics technologies were at a low level (TRL 3). As with prior products, it was purchased from foreign experienced firms.	FBW flight control system in pitch and yaw axis, and hybrid FBW/hydro-mechanic roll axis. Embraer has, through subcontracts, purchased this technology. Embraer shares its knowledge regarding control laws with the partnership.

(continue)

Exhibit 2. **A comparative table of data collected during interviews** (conclusion)

Topic	INPE MUX Camera case study	Embraer fly-by-wire case study
Technology development	Optics technologies were developed together with product development contract (TRL 4 to 9), without prior technology experiments (TRL 4 to 6).	Primarily, Embraer had bought knowledge (E1) and then developed the knowledge (after E1).
Desired capability	How to develop and integrate medium-resolution cameras; how to develop and manufacture optical lenses and components.	How to develop FBW software and control laws; how to integrate a FBW full system.
Resource allocation	INPE responsible for medium-resolution camera integration. Creation of a team dedicated to integrate remote-sensing cameras and develop space optical lenses and components inside Opto.	Creation of a team dedicated to develop FBW inside Embraer through internal reallocation and hiring.
Movement in the industry value stream	INPE moved upstream from systems integrator to subsystems integrator for medium-resolution cameras. Opto entered space applications market as a subsystem manufacturer.	Embraer moved upstream from systems integrator to subsystems integrator for FBW, and upstream for software development.
Project management key indicators		
Schedule goals	High deviations from original baseline.	Low deviations from original baseline.
Budget goals	High deviations from original baseline.	Low deviations from original baseline.

RESULTS

Founded in 1969, Embraer SA has become one of the world's largest aircraft manufacturers, focusing on specific market segments and with great potential for growth in commercial aviation, executive aviation, and defense and security (Embraer, 2016).

INPE is a research unit of the Brazilian Ministry of Science, Technology, Innovation, and Communication (Ministério da Ciência, Tecnologia, Inovação e Comunicação) created in 1961. Its mission is to foster science and technology in the context of earth and space and be able to offer products and regular services for the benefit of the country (INPE, 2016).

CASE STUDY: BACKGROUND OF EMBRAER'S FLY-BY-WIRE SYSTEM

This paper presents a study of the fly-by-wire flight control system (FBW) and the impacts of its technological maturity (TRL) on the aeronautical industry's competitiveness. The purposeful investment in a particular technology has enabled TRL development.

FBW, according to Spitzer (2011), is a system that controls flight command surfaces of airplanes through electronic signals transmitted to their actuators from embedded computers that interpret the inputs of pilots' inceptors (throttles, sticks, pedals, and levers).

After the introduction of FBW on the Airbus aircraft at the end of the 1980s, the trend of replacing mechanical control by electrical connections has become irreversible (Niedermeier & Lambregts, 2012). This substitution has become a strong market trend; consequently, Embraer realized that meeting this business need was a key success factor in order to maintain its competitiveness when it was conceiving the EMBRAER 170/190 jet family.

The firm decided to include FBW in the EMBRAER 170/190 jet family at a time when it did not have complete dominion over the technology. In accordance with market requirements, the firm had to accept the risks and uncertainties of this decision. If the firm had chosen not to include FBW, it would be exposed to the risk of not selling enough aircraft to obtain a return on its development investment.

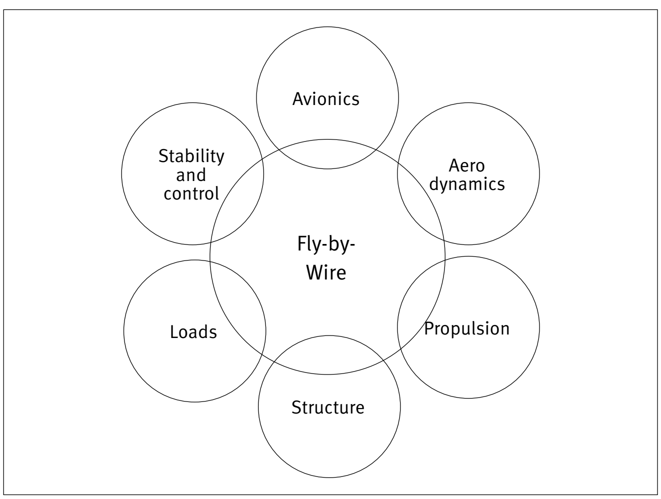
FBW technology is very sensitive for an organization because it involves aircraft control laws; thus, it is a critical technology for an aircraft manufacturer. Moreover, Embraer, which had total control of the dynamic behavior of its aircraft model (TRL 4/5/6), was not in the required state of readiness for this development. Nonetheless, the firm, which had no knowledge of the system's implementation with envelope protection, realized the importance of this technological field (software).

In this context, the lack of experience generated a strong need for internal capability building. The decision to reconfigure Embraer's technology base, turning FBW from the integration domain to the proprietary domain, had an enormous impact on the organization's learning process and was fundamental to its competitiveness and growth.

Embraer had to acquire the technology from subcontractors. At the same time, because of its awareness about FBW's importance, the firm hired senior experts to enable its internal teams to master FBW, thereby generating important cost overruns for the project. Moreover, the firm invested in people, tools, and process developments. As a result, Embraer gained full control of FBW, including all the embedded software.

In an aircraft project, some technologies definitely cannot be outsourced. Because of complexity, mastering the whole development effort is an important way to cope with systemic uncertainty. Thus, Embraer realized that FBW had to be fully developed with its own resources. From the perspective of the Embraer technology development manager, "If we didn't develop FBW internally at Embraer, we would hardly be capable of integrating the aircraft and we would lose competitiveness in the short and long terms". The other technology development manager said, "We cannot depend on partners or suppliers to develop some technologies essential for the survival and competitiveness of this company (...)." Figure 3 illustrates the interactions of FBW with other aircraft subsystems.

Figure 3. **Representative interactions between the fly-by-wire and other aircraft subsystems**



Initially, Embraer bought knowledge and then developed the knowledge. The proprietary domain was considered when the firm managed to combine these two factors. After the capability building in this specific technology, the firm could proceed to another phase, transforming the collective knowledge into a business proposition.

CASE STUDY: BACKGROUND OF THE NATIONAL INSTITUTE FOR SPACE RESEARCH'S MULTISPECTRAL CAMERA

Starting in the 1970s with the NASA Landsat series, remote-sensing satellites began a revolution in new applications and services for society and stimulated global demand for the benefits generated by these satellites. The CBERS system is a series of remote-sensing satellites developed by Brazil and China.

INPE started the technological development of remote-sensing cameras through simulations, breadboard tests in laboratories (TRL 3–4), and engineering models in airplanes to demonstrate their critical functions (TRL 6). At this time, development was focused on systems integration and the technological development of electronic circuitry. Detectors, optical lenses, and components were purchased from experienced foreign suppliers. The technological development of optical lenses and components remained at the analytical/simulations testing level (TRL 3).

The WFI camera was the first Brazilian camera. It was launched in 1999 as part of the CBERS 1 project. This low-resolution camera was developed to account for the country's need for fire and deforestation detection. INPE contracted the Equatorial Company to develop the WFI camera for the CBERS 1 and 2 joint project. The project's organization was in accordance with INPE's development path, whereby Equatorial and INPE focused on systems integration and the technological development of electronic circuitry.

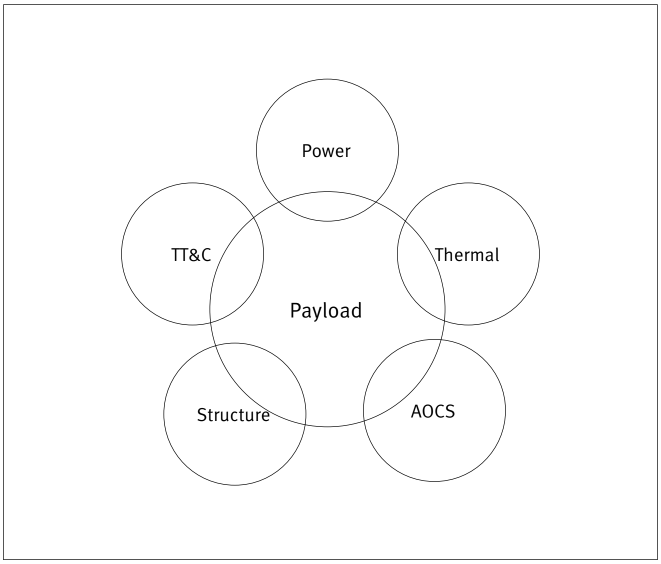
At this point, INPE accumulated knowledge about remote-sensing satellite integration through the CBERS 1 and 2 joint project and by learning from experience, camera integration, and electronics. An opportunity window then opened for the CBERS 3 and 4 payload definitions. Because optics technology represents a very important part of remote-sensing cameras, INPE decided to develop and manufacture optical lenses and components for the next set of cameras together with Brazilian suppliers.

Thus, with regard to the CBERS 3 and 4 project, it was agreed that the Brazilian part of the venture would be responsible for developing a new version of the WFI camera and developing a mid-resolution MUX camera that would replace the charge-coupled device (CCD) camera used in the CBERS 1 and 2 project. In December 2005, a consortium, Opto-Equatorial, was contracted to develop the second-generation WFI camera. Previously, in December 2004, the firm Opto had been contracted to develop a MUX camera. With regard to both cameras, Opto was responsible for developing and manufacturing the optical lenses and components.

Because of the high vibration levels during flights and the vacuum and space radiation exposures during orbit lifetimes, the development of this type of camera requires a meticulous analytical process and the evaluation of optical performance in order to ensure effective operation.

There are also many interactions between a camera and the other satellite subsystems, as shown in Figure 4, which cause emergent properties that need to be understood. Opto had experience with biomedical, defense, and precision optics technologies, but this was the first time that it had developed optical lenses and components for space applications. The system manager of the INPE MUX and WFI cameras said that "It was very important to previously understand the interactions between the camera and the rest of the satellite in order to perform the desired remote-sensing system functionality."

Figure 4. **Representative interactions between the payload and other satellite subsystems**



Notes: TT&C refers to the Telemetry Tracking and Command subsystem; AOCS refers to the Attitude and Orbit Control subsystem.

INPE, Opto, and Equatorial succeeded in delivering MUX and second-generation WFI cameras for the CBERS platform launched in 2014. Both types of camera were operational and met requirements. Nonetheless, the original schedule was for delivery in 2008. The projects needed to have cost and schedule extensions due to the optical technology and product development.

ANALYSIS

We analyze the evolving technological paths from one generation to the next through both case studies, considering systems integration as an instantiation of dynamic capability and using the proposed "coupled processes" model to frame the analysis.

In both case studies, architectural knowledge was important in order to convert subsystem technologies that were in the integration domain into proprietary domain technologies. In this regard, the timeframe and granularity are important aspects for a better understanding of organizational change (Helfat & Winter, 2011). Through the two in-depth case studies, we demonstrate that architectural knowledge (Henderson & Clark, 1990) creates many important technological opportunities for systems integrators, allowing them to redefine their value-creation strategies (Barney, 1991; Peteraf, 1993). As presented in Figure 2, in both case studies upstream movement regarding subsystems' development in the second generation was preceded by mastering the architectural knowledge of the lower hierarchical level (n-1) into the systems (n) of the first generation.

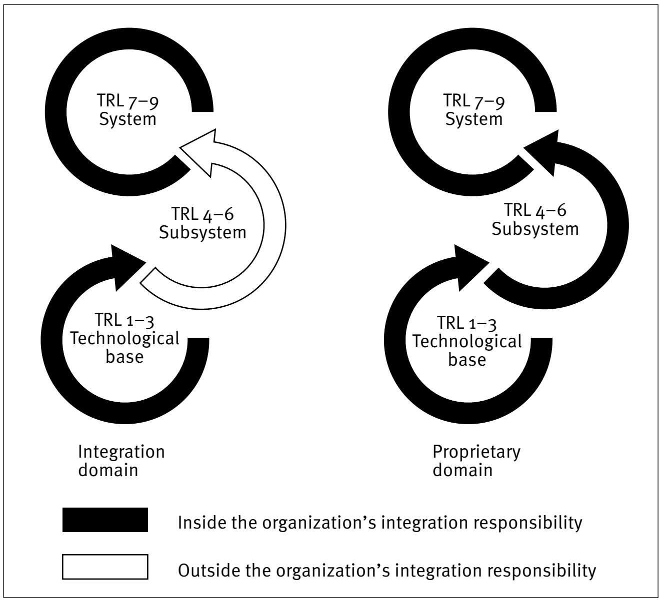
We argue that in order to analyze the depth and width of technological learning (Teece et al., 1997), a metric should be incorporated to guide decision-making processes. The metric considered is TRL. This metric is applied to different instantiations of dynamic capability: new product development and technological development.

Moreover, we propose that in CoPS industries, a firm's technological base consists of a proprietary domain and an integration domain. Since our lens is organizational, we propose the "coupled processes" model to unveil the business of systems integration. The "twin processes" of vertical integration or disintegration depend on the rates and directions of organizational learning (Hobday et al., 2005). If the "twin processes" explain the search for a better position in the industry value stream, decision-making regarding integration or disintegration stem from the "coupled processes."

From the systems integration depth of knowledge perspective, we can observe in both case studies that taking responsibility for subsystems' integration was a key feature that characterized the reconfiguration that occurred in value-stream repositioning, or the transition from integration domain to proprietary domain in accordance with the proposed model.

INPE took responsibility to integrate the medium-resolution camera subsystem by establishing a development contract with Opto. Embraer started developing in-house FBW software and took responsibility to integrate the full FBW subsystem. Figure 5 illustrates this key feature.

Figure 5. **Technology readiness levels and systems hierarchy integration responsibility**



In Figure 5, TRL 4/5/6 levels represent the subsystems' integration capacity in terms of the lowest level of Gholz's (2003) taxonomy. Figure 5 also highlights whether the technologies are in the integration or proprietary domains.

The proprietary domain is critical for firm-sensitive technologies. At certain times, this knowledge can be bought; however, to acquire the proprietary domain for a specific technology, a firm has to achieve its own proficiency. "Short cuts" cannot be undertaken.

March (1991) argued that the initial movement in a new project database starts with exploratory learning; in other words, when a firm explores new ideas and innovative combinations of pooled resources and capabilities in a vanguard project. This model is similar to the way in which Embraer sought to accelerate its learning in the FBW development project.

In the case of INPE's second-generation CBERS platform, new product development overlapped with technological development, heavily influencing schedule slippage and cost overruns. These negative results were not observed for the second generation of EMBRAER 170/190 jets. Here, FBW development preceded the new product development process. This difference points to the advantage of having technological development and product development as separate processes as opposed to an overlapping process.

In the most advanced capitalist countries, forward vertical integration is more frequent. Such integration always seeks a closer relationship with the customer through the supply of services, an approach that creates more value for new projects. However, in both case studies herein analyzed, we found backward vertical integration.

Researching the NIE context, Teece (2000) suggested that, "(...) if firms make the commitment to acquire it (a technology) and establish the managerial processes to facilitate the absorption and integration of technical and industrial knowledge inside the firms" (p. 123), they can catch up with the technological frontier. In both case studies, this argument may help to understand the reason for backward vertical integration instead of the forward vertical integration that is frequently observed in advanced capitalist countries. Thus, we propose that the "coupled processes" model may be very useful for tackling these issues, especially for organizations dealing with CoPS industries in NIEs.

In both case studies, dynamic capabilities ensure that project capabilities are adapted to environmental changes. According to Davies and Brady (2015), new resources may arise to develop vanguard projects on the border of innovation, where new expertise, rules, and principles challenge routines and practices.

By making an incremental innovation in the second generation from a prior operational generation, both firms were able to improve their learning processes in accordance with Teece et al. (1997): "If many aspects of a firm's learning environment change simultaneously, the ability to ascertain cause-effect relationships is confounded because cognitive structures will not be formed and rates of learning diminish as a result" (p. 523).

From the absorptive capacity standpoint (Cohen & Levinthal, 1989, 1990), such capacity, which was explored mainly in the integration domain, helped Embraer and INPE to sense and seize their opportunities (Teece, 2007).

The reconfiguration (Teece et al., 1997) at Embraer and INPE occurred with their upstream movements in the industry value chain. Embraer reallocated resources, thereby creating a dedicated group for FBW development. INPE became responsible for the integration of medium-resolution camera subsystems. The reason for this reconfiguration in both cases was to explore technological opportunities and be able to seize them, and to remain competitive in the long term.

Considering the concept of ambidexterity (O'Reilly & Tushman, 2008) as the ability of a firm to explore and exploit simultaneously in order to adapt over time, we can assume that by developing first-generation products in the integration domain and second-generation products in the proprietary domain, Embraer and INPE were able to present ambidexterity, thereby exploiting their markets and at the same time exploring new technologies and features.

Systems integration can also be understood as a hybrid industry coordination mechanism, where the dominant design may not exist, because it has characteristics of both vertical integration and market coordination. The "coupled processes" model emphasizes the cognitive intertwining of new product development's and technological development's organizational processes, emphasizing the relationship between dynamic capabilities and ambidexterity. The model is especially useful for NIE organizations that have gaps in their technological bases, although they are able to develop products at the technology frontier. This situation emphasizes the importance of a systems integration strategy.

Moreover, the set of dynamic capabilities needed to adapt to changes is not universal; however, firms need to choose their modes of adaptation in accordance with their settings and heritage (Birkinshaw, Zimmermann, & Raisch, 2016).

CONCLUSION

The proposed "coupled processes" model contributed to this study as a frame to analyze the evolving technological paths from one product generation to the next in both case studies in the Brazilian aerospace industry, considering systems integration as an instantiation of dynamic capability.

The "coupled processes" model enables the depth of technological development to be quantified and presents a composition of technologies, consisting of the proprietary domain and the integration domain. Systems integrators' technological base shaping was also unveiled using TRL, as proposed, with the model.

With regard to systems integration analysis as a coordination mechanism between vertical integration and the markets, the proposed "coupled processes" model may be a useful analytical model. When a change occurs in an industry value stream, this model provides decision-making yardsticks associated with vertical integration, vertical disintegration, and the definition of responsibilities regarding subsystems integration.

The case studies presented examples of backward vertical integration in their industry value streams. It is interesting to analyze this different path, which contrasts with the usual approach taken in advanced industrialized economies. Based on the NIE literature, we suggest that the "coupled processes" model may be a useful evolving technological path for NIE organizations, enabling them to catch up with the technological frontier.

Because the set of dynamic capabilities needed to adapt to changes is not universal but depends on firms' settings and heritage, the "coupled processes" model is revealed as a set of dynamic capabilities that has been identified in both case studies in the Brazilian aerospace industry. The model presents ambidexterity, thereby helping organizations to deliver necessary changes along a cost effective and strategically planned path.

Hence, the contribution of this paper to dynamic capabilities theory is to reveal the "coupled processes" model as a set of dynamic capabilities presenting ambidexterity in a CoPS industry, a finding that may be relevant for NIEs.

Because this article presents two in-depth case studies in the particular context of CoPS in an NIE's aerospace industry, its results may be limited in terms of generalization to other contexts or industries and even within the same industry of an NIE. Thus, the authors suggest that future research should investigate new case studies that present upstream movements in the value streams of CoPS industries and offer theoretical and empirical research on dynamic capabilities and systems integration in the NIE context.

AUTHORS' NOTE

Interview forms used for data collection can be requested from the authors.

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