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Systems Architecture, Procedural Knowledge and Learning by Using: Implications on Systems Integration Capabilities

Milton de Freitas Chagas Junior
E-mail address: milton.chagas@inpe.br
Centro Universitário das Faculdades Metropolitanas Unidas - FMU
Rua Taguá, 150, Liberdade, 01508-010, São Paulo, SP, Brazil.
Instituto Nacional de Pesquisas Espaciais - INPE
Av. Astronautas, 1.758, Jd. Granja, 12227-010, São José dos Campos, SP, Brazil.

Milton de Abreu Campanário
E-mail address: macampanario@uol.com.br
Universidade de São Paulo – FEA/USP
USP, Av. Prof. Luciano Gualberto, 908, 05508-900, São Paulo, SP, Brazil.

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Abstract

The objective of this article is to assess the implications of systems architecture on the establishment of organizational learning cycles, and its influence on possible forms of process integration. Dynamics of innovation of complex systems do not follow the pattern of mass-production industries. In complex systems industries there is no dominant design and each new product generation remains in a fluid phase. This article focuses on analysis of the dynamic phenomena that occur when a system performs its functions within the operational environment. By considering successive generations of the China-Brazil Earth Resources Satellite (CBERS) platform as a case study a stylized cognitive model is presented. It is argued that learning by using is practice-oriented epistemology to the extent that it requires the reflective confrontation of a previous stock of knowledge with that derived from praxis, which is concrete, dynamic and relational. Knowledge generation derived from learning by using – tacit and explicit – crystallizes a common knowledge base, allowing the refinement of subsystems designs and interfaces through successive generation of products. Systems integration capability building requires a project-based organization in order to merge operating and learning processes in a multifunctional framework.

Key words: innovation in complex systems; procedural knowledge; systems integration capabilities; emergent properties; learning by using.

Introduction

Innovation in complex systems shows many specific and important characteristics that differ from traditional innovation in mass -production systems. Rosenberg (1976) was the first to recognize the need to establish research streams aimed at modeling dynamics of innovation in complex systems, stressing the importance of balancing advances in technological disciplines incorporated in complex systems. Systemic uncertainty and the relevance of learning by using to successful innovation in complex systems are framed in Rosenberg (1982). During the past fifteen years, since the formalization of an innovation model ideally developed to deal with dynamics of innovation in complex systems (Hobday, 1998), many researchers are finding creative ways to strengthen this theory (Brady, Davies, & Gann, 2005; Brusoni, Prencipe, & Pavitt, 2001; Chagas, Cabral, & Campanario, 2011; Chesbrough, 2003, 2011; Davies & Hobday, 2011).

In this research two different perspectives have been purposefully melded to further analyze distinctive characteristics of innovation in complex systems. The first perspective focuses on the system as a whole, taking into account all components, subsystems and their interdependencies, which make the system more than the sum of its parts. Moreover, system properties do not depend on individually considered subsystems but, instead, emerge from the way the parts interact. Emergent properties are crucial to the concept of a system (Rechtin, 2000; Sillitto, 2005). However, systems can be decomposable from a structural, but not functional, standpoint (Zandi, 2007). This perspective imposes many difficulties in predicting the behavior of a system in its operational environment. Emergent properties may turn out to represent the main functionalities of a system and also compromise the whole system’s functionalities. For this reason, a great deal of attention and effort is dedicated to these phenomena.

The second perspective focuses on capabilities required to organizations that deal with complex systems. A combination of systems engineering and project management processes enables organizations to get systems integration capabilities (Eisner, 2008; Prencipe, Davies, & Hobday, 2003). Organizations must deal with diverse and varied specializations so that these processes facilitate the integration of dispersed expertise in various departments. Forms of interaction between different specialized disciplines are influenced by systems architecture (Eisner, 2005, 2008; Sage & Lynch, 1998). To organizations that deal with complex systems, systems integration capabilities are a kind of procedural knowledge (Johnson, 1997, 2003), exercised in the attainment of real tasks that could not be derived simply by declarative knowledge, expressed explicitly by propositions.

Taken together, these two theoretical perspectives have created conceptual insights to explore the linkage between a significant phenomenon and the creation of organizationally relevant knowledge. These insights show that the traditional knowledge creation model proposed by Nonaka and Takeuchi (1995) limits and distorts our understanding about rates and directions of technical change in complex systems. Investment to convert tacit knowledge into codified knowledge as in the four modes proposed by Nonaka and Takeuchi (1995) are much more related to configuration and information management than to creation of new knowledge. Relying on Dewey (1960) and related works (Cook & Brown, 1999; Gourlay, 2006; Orlikowski, 2002) we explore how a complex system evolves in practice.

Learning by using indicates many possible ways to systems evolution, through the linkages established by the previous stock of knowledge and the flow derived from action, which is concrete, dynamic and relational. Concrete because it considers reality and results from a techno-social construction. Dynamic because it considers elements of actual interaction confronted with the previous knowledge base. And relational because it is rooted in context where praxis and action take place. In order to solve problems and refine solutions this paper argues that these linkages come out of the confrontation between what systems behavior in its operational environment actually is and what it was designed to be. A stylized cognitive model, based on stock-and-flow logic, is proposed to represent this reflective confrontation and its implications to systems integration capabilities building. The development of systems of great complexity will require project-based organization (Hobday, 2000), aiming at capitalizing the knowledge creation that results from the merging of learning and operating processes associated with system-specific architectures. Hence, from the competitiveness perspective, systems integration capabilities bring important implications for organization design and innovation policy.

The research is based on a case study of the China-Brazil Earth Resources Satellite (CBERS) program, established through a project-based organization responsible for definition of systems architecture and the procedural knowledge required for the development of satellite platforms. The most important objective of this international joint project is to capture precise images of Earth. The first most evident failure of the project was an unexpected decrease in the sharpness of the image that came from the main satellite imager. This subsystem was technically well designed, but it turns out to be quite a frustrating experience to learn that well-designed subsystems don't necessarily lead to a good end product. Rather, something else is needed. In this project, learning by using is analyzed from the perspective of practice-oriented epistemology and is considered an important element of systems integrations capability building, allowing **systemic uncertainty** to be transformed into manageable risks, through successive generations of satellites within the same systems architecture.

This study is organized in six sections, besides this introduction. Second section presents the theoretical framework of the article, identifies organizations as integrators of knowledge and emphasizes the peculiarities of innovation dynamics in complex systems. This section also shows the shortcomings of the traditional approach to knowledge creation and argues that Dewey's concepts of knowing and productive inquiry fit well with the peculiarities of innovation in complex systems. Third section explains the choice of case study as a research method. Fourth section analyses the CBERS program, presenting the project-based organization responsible for the development of platform satellites. It also presents the modularity of subsystems: division of labor between the Chinese Academy of Space Technology (CAST) and National Institute for Space Research (INPE), highlighting the phenomenon of emergent properties. Fifth section discusses the organizational conditions necessary for effective learning by using and the challenges of systems integrators. A stylized cognitive model is proposed that represents learning by using as the result of the reflective confrontation between the flow of knowledge that comes from operational practice and the stock of previous knowledge embedded in organizational procedural knowledge. Final section presents article conclusions.

Theoretical Framework

The central problem of innovation in complex systems is how the activities of cooperating specialists are organized to get productivity gains. Although a body of individual specialized knowledge is effectively achieved in purposeful environments, its practical use requires cooperation with other specialists. Cooperation of specialists demands a common knowledge base to take place. Core firms – or systems integrators – are in charge of industry coordination efforts. To do it effectively they must maintain and enhance their integrated learning bases (Chandler, 2001).

Systems integration capabilities and emergent properties

A distinctive role in industry coordination is fulfilled by systems integrators. Each project has its own coordination rules defined by systems architecture. Systems architecture have profound implications on subsequent project phases: development, manufacturing, final integration and operation. "Many systems are highly nonlinear in their behavior, and such behavior may be said to be more complex than the well-known alternative of a (mostly) linear system…Further, our intuition often fails, due to their complex nature" (Eisner, 2005, p. 21).

The basic purpose of system architecture is to define subsystems (or modules) in terms of what they will do and what their interfaces are to other subsystems. Different principles of modular partitioning may follow, aiming at reducing complexity by encapsulating functionalities in specific parts of the system (*e.g.* structured analysis and object-oriented analysis for software systems). A modular architecture allows a subsystem to implement one or few functionalities. There are few well-defined interactions among subsystems named fundamental interactions. Once these interactions are mapped and well-defined it is possible to encapsulate functionalities in some specific part of the system, reducing its complexity. Systems architecture represents important means to mange complexity. In fact complexity is a matter of degree (Simon, 1997). In the very same way, modularity is, as well, a matter of degree (Schilling, 2003).

The extreme of a modular architecture is a configuration where it is possible to isolate functionalities in parts, on a one-to-one basis, with well-defined or standardized interfaces and interdependences. Modular architecture allows a design change to be made in one specific subsystem without requiring change in other subsystems. If a modular architecture is one extreme of a variation spectrum, integral architecture will be the other extreme. Modularity is a relative property of architectures. Systems are rarely strictly modular or integral. Rather, we can say they exhibit either more or less modularity than a comparative system (Ulrich & Eppinger, 2012).

Functionalities in integral architectures are implemented through many subsystems, and interactions among subsystems are ill-defined and may be incidental to basic system functionalities. Other than the fundamental interactions, as complexity grows, incidental interactions may occur (*e.g.* resonance, vibrations, electromagnetic incompatibility and thermal deflection). These incidental interactions may be very difficult to map, especially in innovative architectures. Most of the unpredicted emergent properties result from incidental interactions, which reduce the predictive capacity of defining a system’s behavior in its operational environment. Incidental interactions are sources of systemic uncertainty. Complex systems with very high expected performance and reliability, which are at the edge of what is comfortably known by previous experience, will often be designed with a relative low degree of modularity since implementation of basic functionalities will tend to be distributed across subsystems. Their boundaries may be difficult to identify. When systems are pushing the state of the art, even minor changes in the system may require modifications or redesign of interdependent parts (Eisner, 2008; Ulrich & Eppinger, 2012). Systems integration capabilities combine knowledge of the technology fields underlying the system as well as their interdependence defined in the architecture and materialized in the system when in operation.

Highly innovative architectures demand many different learning processes. Subsystems engineering designs have to be gathered in order to identify incidental interactions. Adequate management of emergent properties is highly dependent on these learning processes and may be realized just after the system is in operation (Pavitt, 2003; Rosenberg, 1982). The recent airworthiness directive order of inspection, expedited by European Aviation Safety Agency to the entire fleet of Airbus A380 jets, due to brackets that connect the aluminum skin of the A380’s enormous wings to its structural ribs, is an example of an emergent property that jeopardizes Airbus operations of the A380 line of production. Rather than being an exception, airworthiness directives are common in the early operational phase of aeronautical systems. They represent the learning by using that is derived from praxis. Catastrophic examples of projects that did not recognize the existence of these subtle interactions is the Comet in the aeronautical segment or Columbia and Challenger in the space segment.

Theoretical proposals that link modular architecture to modular organization in a mix and match fashion, as proposed by Sanchez e Mahoney (1996), seems to overestimate modularization potential. A model that represents dynamics of innovation in complex systems has to consider the presence of a systems integrator that is able to cope with technological interdependence and uneven rates of change in the underlying technologies.

Two models of the dynamics of innovation: mass-production and complex systems

Utterback (1994) argues that a dominant design represents the passage from a fluid phase to a transitional phase in his product life cycle model. In terms of major innovation rate, dominant design represents the point where the process innovation rate overcomes the product innovation rate, as represented in Figure 1. In the fluid phase, management systems tend to be organic due to the explorative character of product design. When a dominant design is defined, the nature of organization changes from organic to mechanistic and it becomes increasingly costly to incorporate product and process changes. From transitional to specific phases, interdependences among organizational subunits grow, and rigid coordination becomes necessary to minimize inefficiencies and costs.

Architectural innovation as proposed by Henderson and Clark (1990) considers that a dominant design will be defined, as is the distinctive characteristic of mass-production industries. Thus, the failure of established organizations is derived from their mechanistic nature, from the rigidities of processes spread among organizational subunits aiming at increased production outputs.

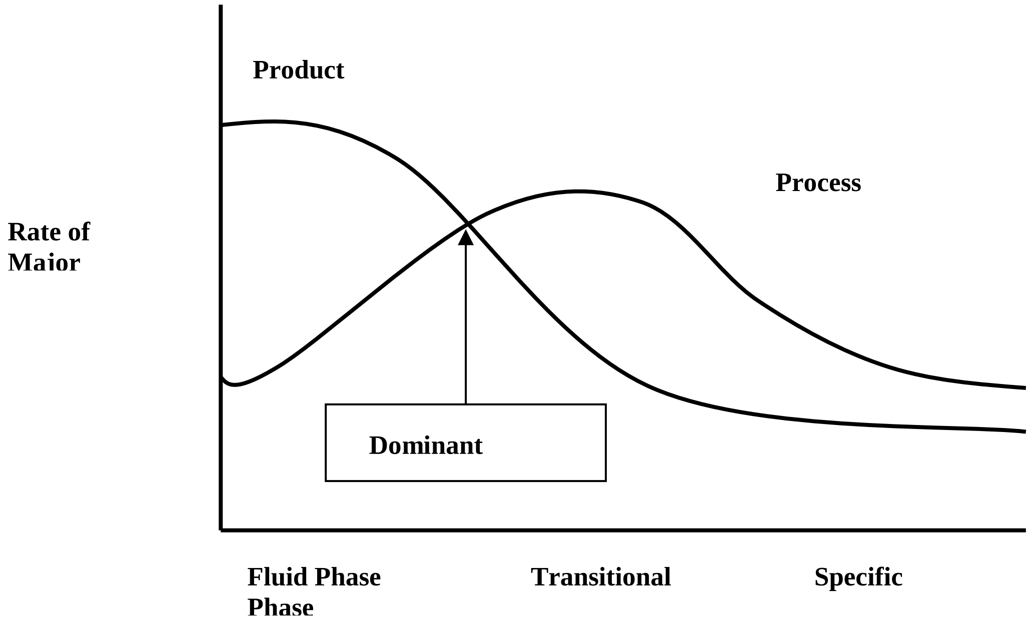

Figure 1. The Dynamics of Innovation.

Source: Adapted from Utterback, J. M. (1994). *Mastering the dynamics of innovation: how companies can seize opportunities in the face of technological change* (p. xvii). Cambridge, MA: Harvard Business School Press.

Different from mass-production industries, in complex systems industries dominant designs are hard to find and dynamics of innovation follow a different pattern. The rate of process innovation is always underneath the rate of major product innovation: organizations do not become mechanistic. Product life cycle is represented just in the fluid phase, through a successive generation of products. (Chagas & Cabral, 2010). As a result, in complex systems industries, architectural innovation catalyses organizational learning cycles through different configurations of systems architecture.

Learning by using is one kind of process that can lead to innovation (Rosenberg, 1982), with pronounced importance in complex systems. Davies and Hobday (2011) argue that innovation in complex systems occur through project-based organizations. These organizations allow the sharing of rising costs and risks of innovation and also promote the reduction of development time (Rothwell, 1994). In the ideal model that represents complex systems industries; architectural innovation assumes a particular importance because there is not a dominant design (Hobday, 1998, 2000). If variation is constrained either by governmental regulation or by limited demand, there will be no dominant design (Tushman & Murmann, 2003).

Chesbrough (2003) suggests that product modularity - characterized by an organizational network of specialized suppliers - does not imply the modularity of technology knowledge. Systems integrators have a wide and deep technology base, and use it to exploit suppliers' knowledge, strengthening the competitive features of the system being created.

The technology advantage of products produced through modular networks is usually defined by the presence of systems integrator firms. “Without very careful effort at developing an appropriate architecture for a system, there will be little hope of integration” (Sage & Lynch, 1998, p. 176). Effective systems architecture aiming at attaining a modular network simplifies the integration effort mitigating the chances of costs overrun, schedules slippage, performance deviation from planned baselines and levels of risk exposure.

In high-technology industries it is possible to identify three levels of systems integration: subsystems, systems and systems of systems (Gholz, 2003). There is a growing specialization in each level of systems integrator. In all three levels, they must be able to properly define systems architecture, divide the work through a modular network of suppliers and be responsible for the final integration. The same three levels are identified by Shenhar and Dvir (2010). Project complexity depends a great deal on the product and grows from subsystem projects to systems of systems projects. In advanced countries, organizations show a growing specialization in each level of systems integration.

Learning by using and systems integration capabilities

Rosenberg (1982) emphasizes that learning by using begins after the start of systems operation and must overlap other learning processes. The *rationale* comes from iterative processes because performance metrics might not be accurately predicted *ex-ante*. On the contrary, some performance metrics of innovative complex systems, frequently cannot be understood before a long experience period in the operational environment (Pavitt, 2003). In this sense learning by using constitutes an epistemology class that is focused on practice, quite distant from the well-known Nonaka and Takeuchi model.

Knowing is the central concept to understand this epistemology class. It is argued herein that this kind of learning - extracted from practice - requires the introduction of the concept of knowing to be properly framed. The conventional model of organizational learning that takes place through the conversion of tacit knowledge to codified knowledge is not enough to tackle this kind of knowledge creation.

We found that investment to convert tacit knowledge to codified knowledge was linked to configuration and information management but not to knowledge creation relevant to the organization. None of the four modes of sequential conversion that define a growing spiral of knowledge creation fit well to learning by using. This research stream requires a practice-oriented epistemology and the concept of knowing as a means to realize that learning by using results from experience itself, from the collective action that takes place in a very well-defined context.

Table 1 bellow, present some studies that use the concept of knowing and present the shortcomings of Nonaka and Takeuchi’s model.

Table 1

Studies that Use the Concept of Knowing as Opposed to Nonaka and Takeuchi’s Model

Author /Year	Study Description	Findings
Cook and Brown (1999)	Authors contention is that there are, in fact, a number of distinct forms of knowledge, and that their differences are relevant, both theoretically and practically, to an effective understanding of organizations. Relying on Dewey, the authors propose that knowledge is something we possess and knowing something we do. Knowing is dynamic, concrete and relational. Dewey´s work is proposed as an alternative to the dominant Cartesian Perspective.	The authors argue that the four modes of conversion between explicit and tacit knowledge form the epistemology of possession. But this model cannot account for the knowing associated with concrete and individual and group action which calls for an epistemology of practice. The generative dance between knowledge and knowing is a powerful source of innovation.

Continues

Table 1 (continued)

Author /Year	Study Description	Findings
Orlikowski (2002)	Orlikowski's empirical context is Kappa, a geographically dispersed high-tech organization. She specifically focuses on groups involved in product development. A central feature of successful product development at Kappa was boundary spanning. Orlikowski adopts a practice lens, allowing her to address individual action and social structure without accepting them as a dualism. She shows substantial conceptual implications in the distinction between knowledge and knowing. Tacit knowledge is a form of knowing and inseparable from action.	The author proposes five practices associated with successful action: sharing identity, interacting face to face, aligning effort, learning by doing and supporting participation. They link these practices to five types of knowing: the organization, the players in the game, how to coordinate across time, how to develop capabilities and how to innovate.
Gourlay (2006)	Gourlay's work inquires the four forms of knowledge conversion: Socialization, Externalization, Combination and Internalization in a spiral process. There is no persuasive evidence that **knowledge** is created by the interaction of tacit and explicit knowledge. Nonaka uses a radically subjective definition of knowledge. By this definition knowledge is created by managers.	Nonaka and colleagues have used an unjustified monolithic notion of tacit knowledge, whereas other authorities argue for and provide illustrations of two types, one that can and one that cannot be made explicit. Using Dewey's concepts it is proposed that different kinds of knowledge are created by different kinds of behavior.

Note. Source: Authors.

Rather than Nonaka's four modes of knowledge conversion, that create a **spiral** of knowledge creation, the evidence supported in this case study is that of iterative learning, confronting a previous stock of knowledge with the one derived from praxis (flow), generating new knowledge which may be either tacit or explicit. Instead of conversion of forms of knowledge, what matters most is the integration of aspects of knowledge among specialized technicians regarding specific purposes. Technicians, instead of managers, create knowledge (Gourlay, 2006).

Reflective confrontation of the previous body of knowledge with that derived from praxis closes a learning cycle by confronting predicted and actual systems behavior in its operational environment. This reflective confrontation is an important mechanism to define the process of productive inquiry used to solve problems. As complexity grows, to define an effective process of productive inquiry is not a straightforward task. To determine deviation from predicted behavior is extremely challenging, since defining and measuring **emergent properties** is done by the means of **project procedural knowledge**, which links many different specialized disciplines. This procedural knowledge is far from being a theory with a precise and general predictive capacity, a feature normally found in declarative knowledge of exact sciences. Tight coupling among the components further complicates traditional "cause-effect" analysis (Zandi, 2007, p. 3). Innovation in complex systems depends on specialized integration knowledge defined through a systemic learning cycle (Kim, 1993).

The same perspective was developed by Polanyi (1958, p. 71). Scientific activity depends heavily on what he calls **procedural knowledge**, the one that comes from action and is "problem-solving". But science relies also on formal rules and depends on the statement of propositions and confrontation with data obtained through research, forming what is known as **declarative knowledge**. It can be better understood following Wittgenstein (1953, p. 104) to whom the "interchange of language-games" gives meaning to words derived from their practical use.

Project procedural knowledge refers to patterns of managerial, technology, and operational practice within the project (Hobday, 1998). **Procedural knowledge** comprises conceptual and operational knowledge, having quite the same meaning as language-games, for both depend on trial and error and are frequently taken out of their proper action environments into quite abstract and conceptual ones, where all practical landmarks and contextual clues and puzzles are removed. Clues are crucial to use knowledge in practice in complex systems. Solutions of puzzles are critical in the way things are put to practical use.

Innovation in complex systems brings about a truthful heuristics: “the more you know about a complex subject, the more you realize how much still remains unknown” (Haimes, 2009, p. 3). Within the same system architecture, this iterative learning allows subsystems design refinement as well as internal and external interfaces refinement. Capabilities are shaped by the elements that constitute the common knowledge base of specialists, formed by detailed communication, “relying on a highly developed and precise common technical language understood by both sender and recipient” (March & Simon, 1993, p. 22). In case of complex systems, common knowledge is created and should be enhanced within **project procedural knowledge** defined by a systems integrator. An extension of the traditional project life cycle is required in order to merge operating processes and learning processes in a multifunctional framework, capitalizing the relevant knowledge creation that takes place derived from praxis and action.

Systems integrators play a “critical role in the evolution of industries not merely as a unit carrying out transactions on the basis of information flows, but, more importantly, as a creator and repository of product-specific embedded organizational knowledge” (Chandler, 2001, p. 2).

Research Method

This research stream proposes a stylized cognitive model, based on stock-and-flow logic, aiming at stressing the importance of praxis and action to systems integration capabilities building. Case studies are adequate to the analysis of specific situations that are representative of many other situations and valid when an expansion of understanding on a subject is required. We recognize that there are many difficulties in developing a theory from a single case study. From this perspective, we suggest that the proposed stylized model is treated as a theoretical proposition. Further rigorous testing based on surveys and multiple case studies are required to analyze how problem solving and knowledge creation take place in complex systems. However, we had unusual access to explore a significant phenomenon that yielded insights of knowledge creation relevant to a project-based organization.

Appropriate theoretical perspectives are of two types. The first refers to the systemic vision and deal with concepts of emergent properties, complexity, modularity, systems architecture and systemic uncertainty. The second refers systems integration capabilities and deals with the melding of systems engineering and project management in organizational procedure knowledge. From these two theoretical perspectives, a research stream is defined to analyze how the problem of solving an emergent property – not planned for and not desired – is solved. That is how new knowledge creation takes place and defines what the implications to organization design are (in this case, a project-based organization) considering the iterative nature of operational and learning processes. The use of Dewey’s pragmatic philosophy has proven to be adequate for the analysis of capabilities of organizations that are involved in the production of complex systems. The analysis of the **emergent properties** phenomenon requires the use of a practice-oriented epistemology.

The case study was selected since it is particularly interesting to analyze problem- solving in complex systems in the context of a project-based organization. This project-based organization, named Joint Project Organization (JPO), as will be seen below, is responsible for the development of Satellites and represents a very interesting example of organizational design that extends traditional project life cycle toward operations.

“The development of products (systems) of great complexity with unpredictable interdependencies and uneven rates of change in the technologies underlying, will require full integration" (Pavitt, 2003, p. 86). The case Study – JPO – is a mission-oriented organization that comprises a program, through a succession of product generations that follows CBERS architecture. Network of suppliers of subsystems are defined for each product generation, coordinated by JPO.

The field research was conducted through two sources: (a) open interviews with INPE managers and researchers directly involved with CBERS; and (b) analysis of related managerial and technical documentation.

The primary data was gained through interviews. A total of 44 interviews were conducted, including: (a) architects who were responsible for the systems design of the program; (b) representatives of the department of contracts and procurement of critical components; (c) end users representatives; (d) technical staff responsible for the execution of the assembly and integration of products and the final tests of these projects. At the public policy definition level, the ambassador who was involved in the issue of international agreements on technological cooperation was interviewed. A first-tier supplier was also interviewed.

Secondary data sources include specialized journals, organizational strategic planning, reports and schedules of the projects that were the subject of analysis, as well as product designs. They also were used to establish the research construct. Three key interviewees were used in order to validate the construct (Yin, 2003): (a) the chief architect of the program; (b) a contract manager; and (c) an engineer responsible for assembly, integration, and final testing. These individuals read and commented on the outline of the case study.

Case Study

Program constitution

Mastering space technology generates strategic benefits within an economic system due to the ability to enhance other industries. Particularly, spin-offs in defense and aeronautical applications are achieved quickly. This is the reason why there are many restrictions on the transfer of technology by the countries that dominate these applications.

The CBERS constitutes an innovative cooperation program between two emerging countries. They have decided to combine financial and technology resources for the development of remote sensing technology. In order to develop the program, a project-based organization was established to house technical and managerial representatives of the INPE and CAST, respectively from Brazil and China. This organization, called the Joint Project Organization (JPO), is responsible for defining the architecture, development, integration and operation of the satellites.

Figure 2 depicts the constitution of the JPO. Inside the JPO, the Joint Project Committee (JPC) is ultimately responsible for program success. It is also responsible for defining general policies, approval of management plans, and translation of the needs of users in high-level systems specifications.

There are Brazilian and Chinese General Projects Managers (GPM). They are responsible for implementing the program. Likewise, the Engineering Technical Group (ETG) and Engineering Management Group (EMG) consist of Brazilian and Chinese technical staff. The ETG is responsible for technical activities at the system level, including mission definition, mechanical and electrical architecture definitions and assembling, integration and test activities (AIT). The EMG is responsible for management activities at the system level, including control of schedule, cost, and development contracts with suppliers of subsystems, and product warranty. ETG technicians define the satellite architecture and its specifications. They are also responsible for specifications below the system level, which define performance, interfaces, and other technical requirements with sufficient detail. This process facilitates detailed preliminary design, followed by the production of subsystems for satellite models.

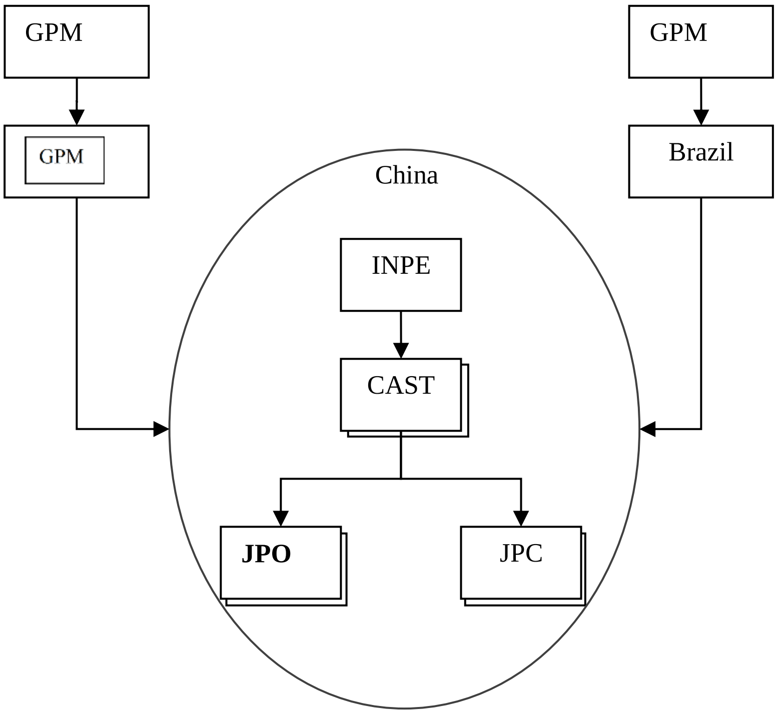

Figure 2. Description of the Joint Project Organization, JPO.
Source: Chagas, M. F., Jr. (2009). *Criação e exercício de capacitações em integração de sistemas – explorando interações entre formas de aprendizagem tecnológica: o caso do programa CBERS* (p. 124). (Tese de doutorado). Instituto Tecnológico de Aeronáutica, São José dos Campos, SP, Brasil.

INPE contracts design and production activities related to subsystems. Bidding processes are used to contract subsystems suppliers. In the guidelines of the bidding there are detailed statements of work (SOW) drawn from the specifications of engineers who are responsible for management of the contract phases.

Systems integration capabilities building: CBERS 1 & 2

Some aspects that are relevant to systems integration capabilities building were objects of concern for the Brazilian group in the preparation phase of the agreement. The activities of assembly, integration, and testing (AIT) of the flight model (FM) and the operation of satellites by the Brazilian side should be highlighted. At the subsystems level, the work was divided according to Table 2 below. It also shows how the division of labor took place among subsystems and the assignment of design authority between Cast and INPE, in the first generation of CBERS. In this first generation division of costs were 70% CAST and 30% INPE.

Table 2

Modularity of Subsystems: Division of Labor between CAST and INPE CBERS 1 & 2

Module	Subsystem	Design Authority
Service Module	Structure	INPE
	Thermal Control	CAST
	Attitude and Orbit Control	CAST
	Wiring	CAST
	Energy Supply	INPE
	On-Board Supervision	CAST
	Telecommunications Service	INPE / CAST
Payload Module	**CCD Camera**	**CAST**
	IRMSS Camera	CAST
	WFI Camera	INPE
	Image Data Transmitter	CAST
	Data Collection System	INPE
	Space Environment Monitor	CAST

Note. Source: Chagas, M. F., Jr. (2009). *Criação e exercício de capacitações em integração de sistemas – explorando interações entre formas de aprendizagem tecnológica: o caso do programa CBERS* (p. 131). (Tese de doutorado). Instituto Tecnológico de Aeronáutica, São José dos Campos, SP, Brasil.

CBERS 1 was integrated in China, as defined in the original agreement. Regarding CBERS 2, in 1993, a complementary term was signed that met two concerns of the Brazilian team. One of these concerns was the completion of the assembly, integration, and testing (AIT) of Flight Model 2 (FM2) at INPE's site. The other was the operation of the satellite by the Brazilian team. This complementary term allowed INPE to develop other systems to track and control the satellite. These items are fundamental to get the 3 levels of systems integration considered in subsection **Two models of the dynamics of innovation: mass-production and complex systems**. Contrary to developed economies, where is possible to identify specialized organizations responsible for each different level of systems integration, in Brazil and in China, INPE and CAST act at the three levels simultaneously.

CBERS 1 was launched into orbit in 1999 via a Chinese Long March rocket 4b from the Taiyuan launch center. The launch of the CBERS-2 occurred in 2003.

Systemic uncertainty arises from the need to integrate different technologies that perform various functions that cannot be completely decoupled within a system. In operation alone, these devices and subsystems do not exhibit any malfunctions. However, when integrated, the interdependence of a piece of equipment or subsystem on the rest of the system or the combination of different subsystems may generate unpredicted and unwanted **emergent properties**. There are techniques to partition or delineate systems architecture so as to reduce the probabilities that these situations could take place.

In complex systems, such as CBERS, many diverse functions are performed just after the final integration, and, therein, combination phenomena are inevitable. Although elaborate techniques can be applied to the decomposition of architectures, some **emergent properties** are only identified during use. Once identified, an analysis of possible cause-effect relationships is performed. This review process proceeds by trial and error because the causalities are not direct. Instead, because of the systems interactions and interdependences, there are many cumulative effects, which create causal ambiguity.

The case of coupling that is presented below can be classified into this category. In light of the experience gained in the operation of CBERS-1, coupling between subsystems were detected. A brief description of this emergent property will follow.

The infrared multispectral scanner (IRMSS) camera, which is a medium-resolution scanning imager, operates on an oscillating mirror in order to scan an image on the various optical sensors, thereby making it a camera scanner. The movement of this mirror was observed to cause certain vibrations and, by means of mechanical coupling between subsystems, made the mirror of the CCD camera (which is in bold in Table 2) become resonant, which decreased image sharpness. For CBERS 2, other tests were performed. The joint analysis of multi-disciplinary team enabled the coupling causes to be identified and removed. It is noteworthy that this phenomenon is not linear, which makes the identification of the cause and effect more subtle, since they do not operate on the same scale. To understand coupling effects and how they propagated through the system in its operational environment was an extremely challenging research effort.

CBERS 3 & 4 – Second generation of the Earth observation satellite

Brazilian participation increased from 30 to 50% for the second generation of CBERS satellites, following the subsystems division of labor presented, in Table 3 below.

For CBERS 3 & 4(1), the knowledge generated by iterative learning was embodied into the design engineering of this subsystem. In CBERS 3 & 4, the MUX camera, which is presented in bold in Table 3, took over the functions that were originally performed by the CCD camera of CBERS 1 & 2.

Table 3

Modularity of Subsystems: Division of Labor between CAST and INPE CBERS 3 & 4

Module	Subsystem	Design Authority
Service Module	Structure	INPE
	Thermal Control	CAST
	Attitude and Orbit Control	CAST
	Energy Supply	INPE
	Wiring	CAST
	On-Board Supervision	CAST
	Digital Data Recorder	INPE
	Telecommunications Service	INPE
Payload Module	PAN Camera	CAST
	MUX Camera	**INPE**
	CCD Camera	CAST
	WFI Camera	INPE
	PAN and IRS Image Data Transmitter	INPE
	MUX and WFI Image Data Transmitter	CAST
	Data Collection System	INPE
	Space Environment Monitor	CAST

Note. Source: Chagas, M. F., Jr. (2009). *Criação e exercício de capacitações em integração de sistemas – explorando interações entre formas de aprendizagem tecnológica: o caso do programa CBERS* (p. 140). (Tese de doutorado). Instituto Tecnológico de Aeronáutica, São José dos Campos, SP, Brasil.

For CBERS 3 & 4, the participation of the Brazilian network of suppliers is 52% of the total resources used by the country. This percentage was achieved through the contracting of design and production of subsystems from Brazilian firms. It is important to note that this percentage increase in Brazilian space industry participation refers to 50% from Brazil, whereas 29% of CBERS 1 & 2 refer to the participation of 30% of the total (Chagas, 2009).

CBERS 5 & 6 – Third generation of the Earth observation satellite

The expected new agreement of technological cooperation between China and Brazil, with 50% for each country, as in the second generation, for the development of the third generation of Earth resources satellites – CBERS 5 & 6 – represents an achievement in the mastering of remote sensing technology for both countries, acting as a powerful tool in development of a space industry standard. Participation of the Brazilian supplier network represents a great deal of the resources used by the country due to the maturity of CBERS architecture.

Analysis

Incidental interaction and emergent properties

The **emergent properties** discussed herein refer to the divergence between the expected and actual behaviors of the system when operation takes place and it interacts with its physical and social environments.

The previous stock of knowledge is iteratively confronted to concrete, dynamic and relational practice – knowing – which may lead to learning by using. This kind of learning is very much linked to the concept of productive inquiry as defined by Dewey: a conscious and active way of pursuing a problem resolution. Productive inquiry represents the way we should establish the interaction between knowledge and knowing, using our previous knowledge as a tool for problem-solving. As pointed out by Nonaka and Takeuchi (1995), complementarities between tacit and explicit dimensions of knowledge are what matter most in practice.

In the current case, there was a discrepancy between the expected quality of the image and the one generated by the main imager of the satellite, the CCD camera, when in operation. The data generated by the camera was received by the control and tracking system. When it was converted into an image through many different Earth observation applications, the achieved image quality presented inferior attributes in comparison to those that were defined in the design of the subsystem. Other than the satellite system, there are control and tracking systems and Earth observation applications to convert data into images. From the outset of research into possible causes of the divergence, performance limitation of the subsystem was considered the main one. Therein, two of the technological disciplines, specifically the optics and microelectronics teams, accused one another of the possible causes. This is a typical situation of causal ambiguity. The cause of the divergence and whether or not the expected level of performance is achievable were unknown, due to the systemic uncertainty. The resonance was an incidental - and nonlinear - interaction between subsystems. A project framework is required to meld learning processes and operational processes into a multifunctional team, allowing effective learning by using to understand the root-cause of emergent properties. This is very different from normal operations with mechanistic features, as represented in the dynamics of innovation of mass-production model. There is a great deal more implicitness in operations processes than is usually represented in the mass-production model. On the contrary, as will be seen below, awareness and reflection are required for problem-solving in complex systems.

Often, it is not possible to establish direct causal relations between events, especially in complex systems. In the context of the CDD camera problem, the conditions for the implementation of the system confronted by repeatedly observed facts - reviewed by a multi-disciplinary team committed to solving the problem - created new organizational knowledge. This multi-disciplinary knowledge base was able to identify some possible causes of the observed problem. This learning derived from a specific R&D effort represented significant improvement for the CBERS 2 performance. This is exactly what Rosenberg stresses in the following passage:

> This is a source of technological innovation that is not usually explicitly recognized as component of R&D process and receives no direct expenditures – which may be the reason it is ignored. **It overlaps with development**. The learning involved requires participation in the production process (Rosenberg, 1982, pp. 121-122, bold added).

It is worth reminding that models are used to describe what the system ought to be. By definition, models represent reality in a simplified way. Every model has simplifications of reality precisely because not everything that is necessary to describe a situation is known. An efficient model reproduces data in a satisfactory way for the established purposes. That is to say, there are many factors that may be considered irrelevant to these established purposes. Models are **interchange of language games**, built specifically to deal with our bounded knowledge of the natural and artificial world.

Reflective confrontation between stock and flow of knowledge

The origin of the analyzed events depends on the teams that designed, developed, integrated, launched, and operated the satellites. Figure 3 presents the iterative learning between the previous stock of knowledge and the flow of knowledge which is concrete, dynamic and relational, derived from praxis and action. The stock of previous knowledge is represented by organizational processes and by project procedural knowledge. Space engineering begins the establishment of project procedural knowledge, based on the previous body of organization procedural assets. In order to define systems architecture, engineering must be in contact with segments of the launch, attitude, and orbit controls and Earth observation, which defines final user requirements (Chagas & Cabral, 2010). Once the architecture is defined by JPO, engineering subsystems design and production is assigned to a supplier, following the modularity of subsystems defined in Table 2 (CBERS 1 & 2) and in Table 3 (CBERS 3 & 4).

Integration of subsystems is done through JPO supervision. The operation occurred through teams that controlled orbit and attitude and teams that converted data into images, which is an Earth observation attribution. The divergence between the qualities of the generated image from that predicted by subsystems design started intensive interaction between these teams. Available procedural knowledge is confronted by concrete, dynamic and relational reality. This process created the conditions for the discovery of the root-cause of the divergence between the expected and observed behaviors. Thus, iterative learning, which is required for the refinement of design, depends on the integration of previous knowledge base and knowing. Feedback looping increases and refines both. It increases and refines the knowledge base – tacit and explicit - as well as increases and refines knowing - knowing how to innovate (Orlikowski, 2002).

Although traditional knowledge management focuses on a type of knowledge that people have, *i.e.*, the epistemology of possession, iterative learning must be understood as a practice-oriented epistemology (Cook & Brown, 1999). This requires iteration of previous stocks of knowledge and knowing – concrete, dynamic and relational. At the launch of the CBERS 2, the element that was resonant with the IRMSS camera vibration was removed, although the engineering design of the subsystem had not been changed. This occurred because the subsystem had already been produced. In fact, when the problem was discovered, the CBERS-2 project was in its final phase of integration and testing. This knowledge was embodied into the development of the MUX camera of CBERS 3 & 4. In this project, the engineering design authority of the camera that was equivalent to the CCD, which is now called the MUX camera, moved to the Brazilian side, as shown (in bold) in Table 3, under a company contracted by INPE called OPTO. In this case, learning by using takes an embodied form, directed at development via the incorporation of new knowledge, created through learning by using, in the subsystem engineering design.

The incorporation of this new knowledge into the subsystem engineering design also represents a characteristic of cumulative technological knowledge. Research efforts that allow the establishment of the learning cycle are accumulated over a certain innovation path and follow rules that are determined by the systems architecture. The possibilities of incremental and modular improvements to the system are severely constrained by forms of perception that are shared by the project teams (Rechtin, 2000).

Emergent properties of complex systems decrease the ability to predict system performance in the operating environment (Hobday, 2000; Sage & Lynch, 1998). This occurs because the number of interactions between system components exponentially increases with the number of components, allowing many new and subtle types of emergent behaviors (Eisner, 2005).

In the current case, we observed mechanical coupling between the CCD and IRMSS cameras. This coupling was because the vibration frequency of the scanner was approximately equal to the resonant frequency of the spring supporting the mirror of the CCD. In a hindsight perspective, after the learning cycle is established, this problem may seem obvious. But it is not. Intuition about new problems often fails. The complex nature of problems leads to causal ambiguity, which is a characteristic of systems with nonlinear behavior. Many tests were introduced in integration phase to try to avoid similar problems. These new tests cost money and take time to perform. Budget and schedule pressures play against the introduction of these tests.

Multifunctional teams committed to systems evolution are those who define what should and what should not be done. The flow of relevant knowledge, that allows the integration of knowledge, enhances the crystallization of a common knowledge base - tacit and explicit. A project-base organization provides the integrative environment to link operational and learning processes.

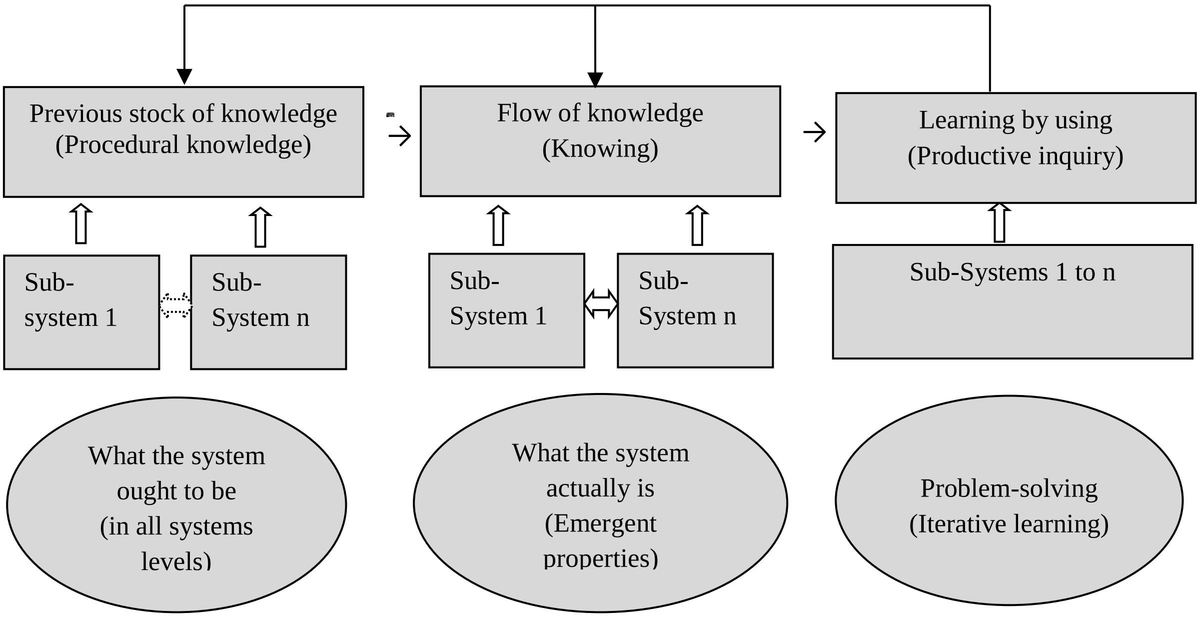

Figure 3. Reflective Confrontation between Stock and Flow of Knowledge Generating Learning by Using.

Source: Authors.

Learning by using, considered as the reflective confrontation of a previous stock of knowledge and that derived from praxis, creates a cumulative effect that is associated with systems architecture, as represented in Figure 3. “The notion that thought, apart from action, can warrant complete certitude as to the status of supreme good, makes no contribution to the central problem of development of intelligent methods of regulation” (Dewey, 1960, p. 36). The more innovative the architecture is, the more it is subject to unpredicted **emergent properties** in complex systems industries.

Extension of traditional project life cycle and iterative learning

In terms of economic value creation, these incremental innovations, which are derived from problem-solving, are extremely significant. Complex systems projects require an extension of the traditional life cycle to include operations activities, aiming at economic value creation. The learning cycle proposed by Chesbrough (2011) is very similar to that proposed by Brady, Davies, and Gann (2005) and Davies and Hobday (2011), all of whom emphasize the growing importance of learning by using, linking operational and learning processes, through the provision of services to the final user.

Systems integration capabilities must be seen from a dynamic point of view. They allow the organization to move from one generation to another, aiming at a better position in the value stream of an industry at any given time (Hobday, Davies, & Prencipe, 2005). This dynamic perspective is necessary to identify innovation paths based on systems architecture.

When systems architecture is well-known and complexities are well understood, an organization developing a next generation of a product can predict many aspects of systems performance and accurately estimate costs and schedule in a manageable exposure of risk. In the words of Nelson (1996):

> A particular problem in R&D on multicomponent systems arises if the appropriate design of one component is sensitive to the design of other components. Such interdependence militates against trying to redesign a number of components at once, unless there is a strong knowledge that enables viable designs for each of these to be well predicted ex-ante, or there exist reliable tests of cheap models of new systems (Nelson, 1996, p. 153).

Contrary to theoretical propositions to link modular organization to modular products, **in mix and match fashion**, evolution of complex systems have to be carefully coordinated, especially when choosing innovative components, parts and subsystems that reduce the predictive capacity of systems when in operation environment. When ripple effects are easily mapped into manageable configurations spaces, confidence in projects deliverables grows. Derivative and retrofitting projects can be exploited by the organization and many economies can be withdrawn from systems architecture. The ultimate test of systems architecture in its co-evolutionary change is represented by longevity, allowing technical improvements that positively respond to stakeholders needs.

Following this *rationale*, the new agreement of technological cooperation, for the development of CBERS 5 & 6, will use the purchasing power of government as an effective tool of industrial policy, with a growing participation of the Brazilian supplier network, due to the higher level of architecture maturity achieved by CBERS platform, which has been defining an innovation path in space industry. CBERS 5 & 6 will have a prevalent commercial character while the previous generations had a prevalent R&D character. Systems integration capabilities associated with this architecture allow the transformation of **systemic uncertainty** into manageable risks, within established confidence limits by meaningful assignments of objective probabilities. These capabilities bring many opportunities to the expansion of international business involving CBERS platform.

It must be considered that any system architecture has performance limits. The form of subsystems integration that defines the systems architecture will sooner or later constrain technical advance. Then, a new architecture must be found. That is a much more demanding effort than innovating within a given architecture (Chesbrough, 2003), since organizational processes must be integrated in different ways, and a new forms of learning have to be found to define a new cycle. Moreover, systems architecture may cause an exclusion effect, limiting and guiding what has to be done downstream (Rechtin, 2000).

In the absence of a dominant design the difference between these forms of learning is well framed by Kim (1993, p. 94) in his systemic model of two cycles of learning: single-loop and double-loop cycles. New systems architecture requires the establishment of a different “interchange of language-games” to be embedded in **project procedural knowledge**. New systems architecture imposes different constraints and commitments to researchers who will be following different rules, in each of the three levels of systems integration herein considered.

Conclusions

The analysis of the satellite program CBRES demonstrates the adequacy of considering learning by using as a result of the reflective confrontation between the previous stock of knowledge, accumulated through organizational processes, and knowing, derived from concrete, dynamic and relational experience. This confrontation creates the conditions to better understand complex systems in the operational environment. The stylized cognitive model herein presented shows that learning by using may be conceived within Dewey’s pragmatic view of productive inquiry.

We have been arguing that systems integration capabilities building depends on learning by using and is associated with specific architecture. A practice-oriented epistemology overcomes the shortcomings of possession epistemology as considered in the traditional forms of knowledge conversion. Learning by using creates conditions to identify and to measure unpredicted (and sometimes unwanted) **emergent properties** that threaten systems performance. The process of productive inquiry represent an important means of subsystems design and interfaces refinement that must be integrated in a specific architecture. In the case of CBERS these capabilities have been allowing a progressive better position of INPE in the space industry value stream.

This article draws attention to the need to extend the traditional project life cycle into the operational phase in complex systems industries. The procedural knowledge that arises from learning by using indicates possible paths of innovation. Learning by using crystallizes a common knowledge base of specialized technicians and tends to have increasing relevance in the designs and interfaces refinement of complex systems.

Systems integration capabilities, associated with specific systems architecture, are required to transform **systemic uncertainty** into manageable risks. In light of these challenges, one should not consider that the modularity of products implies organizational modularity in a mix and match fashion. On the contrary, in the face of complexity, a common knowledge base that permits multifunctional teams to work effectively takes time to form. It is this common base that will allow the integration of aspects of knowledge that are relevant to that kind of interaction among specialist teams, which may be tacit or explicit in nature. In the absence of a dominant design, systems integration capabilities are even more strategic to the coordination of complex systems industries than in mass-production industries.

A systems integrator, as a repository of product-specific knowledge, has to take care of **project procedural knowledge**, considering the implications of iterative learning in configuring – and reconfiguring – innovation networks in order to effectively harness the benefits of learning by using.

In addition, it is concluded that capabilities in systems integration are an effective strategy for bridging technological gaps. As organizations compete in an increasingly connected world, systems integration capabilities become more valuable to the success of technological innovations.

Note

[1] The December 9th, 2013, launch of CBERS 3 failed. The Long March 4B rocket was not able to properly insert CBERS 3 into the planned orbit. The root-cause of this emergent property - unplanned and undesired – has not yet been identified. This new fact, which took place after this article was approved, confirms what the authors have been arguing: that learning by using must consider **knowing** - the flow of knowledge derived from praxis and action - as confronted with a previous stock of knowledge, in order to be effective. The launching of CBERS 4 is anticipated and should happen within 14 months. This is the amount of time required to assemble, integrate and test (AIT) activities. CBERS 3 & 4 are identical, so what has been exposed in the case study is valid for both satellites. To produce two identical satellites in each generation represents, among other things, a means to deal with high-risk projects.

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