Interrupted Innovation: Innovation system dynamics in latecomer aerospace industries

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Abstract

In this paper we develop a dynamic sectoral innovation systems framework to analyse the emergence and catch-up of aerospace industries in latecomer economies. Aerospace manufacturing requires very advanced technological capabilities at early stages of development, due to the need to meet high international quality standards. Stage models of technological upgrading are not appropriate to describe the evolution of this specific industry in latecomer economies. We show how successful latecomers have developed mechanisms to provide the sector with the capabilities to compete on a continuous basis. We also show how competitive pressures periodically require the industry to reinvent itself almost from scratch in a process of interrupted innovation.

We argue that as infant aerospace industries mature and face increased competition, the underlying national-sectoral innovation system undergoes both gradual expansion and radical transitions. After periods of gradual expansion along a given trajectory, the innovation system undergoes interruptions which radically affect the institutional framework, the relationships between actors in the system, as well as strategies and policies.

With the help of historical evidence from Brazil, China and Indonesia, we show how changes in the global competitive landscape or major political developments trigger periods of crises in the industry, which the existing systems of innovation are unable to cope with. The innovation system itself needs to transform itself. We provide a qualitative analysis of the nature and speed of innovation system transition in selected historical cases of success and failure. We conclude that the emerging economies which succeed in catching up in aerospace are those that have established a competitive industrial segment supported by a sectoral innovation system which is able to adapt flexibly to radically change circumstances, expanding its size and changing its characteristics.

Keywords: aerospace manufacturing, sectoral innovation systems, system dynamics, technological capabilities

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1. Introduction

1.1. Innovation as an engine of growth; emerging economies in the global aerospace industry

Industrialization has been a primary source of accelerated growth for advanced economies and emerging countries alike. Szirmai concludes there were “no important examples of success in economic development in developing countries since 1950, which have not been driven by industrialization” (Szirmai, 2009:35, Merit WP), Verspagen and Fagerberg (1999) found evidence that manufacturing was an engine of growth in East Asia and Latin America. Some latecomer entrants into high-tech industries (think of South East Asian tigers and their entry into electronics) have benefited from higher value added output ratios associated with the technology-intensive production (Fagerberg, 2000). Contributions in the tradition of the new growth theory (Romer, 1986 or Grossman and Helpman, 1991) and evolutionary economics (Nelson and Winter, 1982, Dosi et al, 1988) proved theoretically and empirically the link between innovation, technological change and economic growth. A careful look at what lies ‘inside the black box’ of technology and innovation following Rosenberg (1982) revealed the crucial role of historical context and institutions. The development of national technological capabilities required for industrialization was found to depend on the interplay of incentives, capabilities and institutions, should any of which fail, corrective intervention is needed (Lall, 1992). The challenge to respond to the analytical and practical challenge of studying technological change in its complexity and providing comprehensive development policy advice to policy practitioners inspired the emergence of the innovation system literature (Freeman, 1987, 1995, Lundvall, 1992, Nelson, 1993).

For decades, it has been dominated by first mover manufacturers from North America, Western Europe and the Soviet Union. Over the second half of the 20th century, mainly driven by military considerations (Goldstein 2002), a number of newly industrializing countries have attempted to set up production facilities, among them Argentina, Brazil, India, Indonesia, Israel, South Korea, South Africa and Turkey as well as P.R. China, Singapore and Taiwan. Following initially mixed results, a few emerging countries, including Brazil and China, have successfully developed their capabilities for aerospace production and have entered the global market. Our evidence shows that they have experienced accelerated growth and catch-up in aerospace industries. Catch-up is understood here as a narrowing of the technological gap resulting in substantial gains in global value added shares of latecomer economies compared to their advanced country competitors.

Figure 1 compares the emerging countries with the leaders. Compared to the United States, aerospace manufacturing value added in emerging countries hardly amounted to 3% in 1990 but grew to 13% by 2000 and to nearly 20% by 2005. Figure 2 focuses more on dynamics of latecomers. In terms of sales volumes these countries have overtaken incumbent producer countries such as France and Italy by the year 2000. They are now challenging Canada and Japan. The share of emerging countries in global value added doubled in a decade to nearly 10% by 2005 and continues to increase. The most successful of the late entrants, Embraer of Brazil is now among the top five
commercial aircraft manufacturers in the world. The figures for China need to be regarded with caution. Chinese aerospace conglomerates produce a range of products outside the aerospace classification. If commodity based figures were available similar to what is reported for Brazil, Chinese value added would presumably be less than that of Brazil at the turn of the millennium. The fact that Brazilian value added has recently been declining, even when Embraer’s turnover has been growing, indicates that the sector is facing a challenge.

**Figure 1** Value Added in Aerospace Manufacturing (1980-2007) (Billion USD at constant = 2000 prices)

**Notes:** Emerging countries include Brazil, P.R. China, India, Indonesia, Rep. Korea, Taiwan and Singapore; Aerospace refers to ISIC Rev.3 class 353; Europe is an aggregate defined by the geographic area.

**Sources:** GGDC and OECD STAN; IBGE, UNIDO, Chinese National Bureau of Statistics, various yearbooks; industry of origin conversion ratios applied from GGDC.

**Figure 2** Value added in aerospace, selected emerging countries (1970-2007) USD Millions at constant = 2000 prices

**Sources:** GGDC and OECD STAN; IBGE, UNIDO, Chinese National Bureau of Statistics, various yearbooks; industry of origin conversion ratios applied from GGDC.
1.2. Specific features of the aerospace industry
The aerospace industry has some highly distinctive features. Hardly any other industry experiences demand fluctuations which are so closely correlated with the evolution of global GDP as aircraft manufacturing. Producers need to be prepared for cyclical changes in demand and regularly returning crises within the lifetimes of their products. Aerospace manufacturing is a leader in technology intensity (Smith, 2005) and is highly capital intensive. New entrants face a steep learning curve (Frischtak, 1994). In aerospace access to technology for latecomers is limited by the immense costs of entry rather than patents. The industry is characterized by imperfect competition, non-homogenous products and economies of scale. Fixed initial development costs are to be recovered during short production runs of a small number of products (Beaudry, 2001). To overcome the underinvestment in new technology, manufacturers rely on some sort of government support, either through launch or export subsidies, military procurement or market protection. To justify their actions, governments argue along the lines of national security, prestige and expected spillovers 2 to downstream industries and services and other sectors of the economy. In any case, aerospace is at the intersection of industrial, higher education, science and technology and innovation policies. The global aerospace industry has undergone a number of transformations throughout the second half of the 20th century. The arrival of the jet age in the 1950s, the increasing global flows of people, commodities and services and the gradual liberalization of the air transport market resulted in rapid growth of air traffic around the world, although primarily between the advanced economies. In the last two decades global aircraft manufacturing experienced a period of shakeout and consolidation, with the emergence of global supply chains and with large-scale mergers and acquisitions taking place in Europe and North America (Nolan and Zhang, 2002). Apart from the traditional industrial clusters 3 , only a few new ones have emerged.

In this paper we develop a framework for the study of sectoral innovation dynamics in latecomer economies, in order to gain understanding in the dynamics of growth and catch up in the successful economies. This framework posits a close association between sectoral innovation system dynamics and the industry’s production performance and growth dynamics. Section 2 discusses the literature on latecomer industrialization. In Section 3, we construct a conceptual framework to compare various modes of innovation system change; in section 4 we discuss a number of case studies. This paper presents a synthesis of the authors’ study of this turbulent industry based on primary field visits to Brazil and China, secondary data and statistical analyses.

2. A perspective on industrial dynamics

2.1. Latecomer trajectories and competitiveness
Historical evidence shows a great variety of trajectories from infant to mature, competitive ones. The strategies governments and firms devised and implemented in

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2 Measuring spillovers effects related to the aerospace industry remains difficult, especially in emerging economies. In the case of the Swedish JAS Gripen fighter program Eliasson (2010) applied a spillover multiplier and estimated that the social returns above the opportunity costs were at least 2.6 times greater than the original investment.

3 For a study on why spillovers favor clusters in the sector, see Niosi and Zhegu (2005).
order to accumulate the capabilities required for the industries to grow varied significantly.

Observers of the successful catch-up of latecomers in high-tech industries in Southeast Asia nevertheless have been keen to find commonalities between the country experiences. While it is fiercely debated whether general lessons can be drawn from the examples (Hobday, 2009), there is a broader consensus how the successful latecomers have reached technologically more advanced stages of production. These observations led to a number of stage models. In Kim’s model (Kim, 1980), South Korean firms had to first implement imported technologies before the scientific and engineering staff could assimilate them and acquired the capacity to improve them. Throughout this process, firms became increasingly competitive, although not without considerable government protection in the early phases. The learning trajectory described by Dahlman et al (1987) spans from production through investment to innovation capabilities. Lall (1982) emphasized that industries progressed from elementary through intermediate to advanced learning capabilities. Hobday (1995:1185) argued that progression is not necessarily linear, since research and development (R&D) may be undertaken at an early stage. Nevertheless, he found a general tendency of firms starting up simple activities systematically and gradually accumulating capabilities to perform complex activities at a later stage. Chaminade and Vang (2008) argue that developing country ICT firms start with competing with low-cost products and advance to become knowledge providers in the global value chain, in which transition a regional innovation system plays a crucial role.

The aerospace industry presents latecomer industrializers with a special challenge because of its technologically complex products. At the core of many of the catch-up models is a tradeoff between quantity and quality. A cheaper but less reliable consumer electronics product can be sold in large numbers, but this is not the case with aerospace products. Quality requirements for firms entering even through the low-end are higher than in any other sector, given the fact that an aircraft or spacecraft is as reliable as its weakest component. Latecomer firms, either manufacturing components or original equipment, can not sell their products unless they meet, from the very beginning, the high standards set by the global industry leaders. Component suppliers’ production processes are meticulously screened by the system assembler company; governments have very limited room to make concessions for newly emerging producers by (temporarily) relaxing standards without jeopardizing public safety (this rule may be overwritten by national security concerns but only temporarily). Consequently stage theories are less applicable to the aerospace industry.

Considering that intensive technological learning and local adaptation took place even in cases where foreign technologies and designs were applied, neither Lall’s advancement of learning stages, Hobday’s increases in complexity, or the production to innovation model of Dahlman et al appear to describe the case of the aerospace industry in a satisfactory manner. The start of series production in aerospace requires firms to already possess advanced learning capabilities, have assimilated and improved a wide range of relevant technologies. Either firms or supporting governments need to have the ability to make huge launch investments. Without successful start of series production, there is no catch-up, without competitive products, there is no series production. Competition requires the production of technologically complex products already at an early stage. Even if these products are
not at the technology frontier, they may be new to the market they are serving. Unless latecomer, state-sponsored producers find buyers other than their respective governments and become sustainable, they will not only become too big a burden for the public to support but their governments will ultimately be forced to purchase high quality products from competitors.

The central question then becomes not what stages a latecomer industry needs to go through along its development trajectory, but rather,

- what set of capabilities it needs to compete in the market segment it aims at the time of entry; and
- how to develop self-sustaining mechanisms to dynamically generate capabilities to continue to compete in a dynamically changing environment?

Firms that succeeded in sustaining their competitive edge over time were innovators. Industries that managed to sustain their competitiveness could not have done it without their supportive environment that offered firms access to resources they required to innovate. The emergence of such sectoral innovation systems appears to provide the key to catch-up for a latecomer industry.

The analysis of aerospace industry evolution starts with an emergent phase in which some countries find an emergent niche for their products. In some countries this is followed by a transition to sustained competitiveness, in other countries the transition fails and the industry languishes.

(I) Emerging industry and innovation system

The emergence of an industry and its sectoral innovation system is a special phase within its overall evolution. If the emergence of an industry in a latecomer economy merely referred to a phase of increased learning, the entire growth phase of an industry’s life-cycle could be coined as the ‘emergent’ phase. What distinguishes the initial phase for our purposes is gradual overcoming of competitive disadvantages stemming from lack of capabilities. It is a phase of reducing obstacles and disadvantages. Latecomer firms face disadvantages in terms of having to overcome both technology barriers and market barriers (Hobday, 1995:1172). On the one hand, they are dislocated or isolated from sources of technology, R&D, and a supply of adequately trained and skilled labor and they lack linkages with advanced country markets that they wish to supply. The firms’ primary aims thus focus on acquisition of technology and access to markets.

On the other hand, being a latecomer offers a potential for accelerated growth and catch-up by being able to avoid the risks, uncertainties and costs of innovation at the frontiers of knowledge, by having access to already available technology and knowledge (Gerschenkron, 1962). But reaping these opportunities and accumulating the required capabilities is a costly process (Perez and Soete, 1988).

Choices facing governments and entrepreneurs in this phase are related to finding a way how to benefit from backwardness and reap knowledge spillovers and rent spillovers. These choices include whether a technology should be acquired from outside or developed locally (‘make or buy’ dilemma), what market segment(s) to focus operations on, what financing mechanisms to set up and how to educate and train scientists, engineers and managers.

It is important to emphasize the evolutionary nature of this phase. Actors have to cope with a high degree of uncertainty, and have to take risks and prepare for an iterative

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4 Market in the case of this industry includes not only civilian but military as well.

5 Although we use the word “phase” here, we emphasize that there is no necessary progressive sequencing.
process. For instance, Hobday (2009) argues with regard to Asian development that what became a success was not foreseen or meticulously planned in advance. Historical evidence varies hugely on the time it takes for an industry to be considered to have left behind the emerging phase, especially because it is hard to find a distinct dividing line. The length of the emergence phase depends on the one hand how successfully the new products sell (initially profiting from subsidies and government support) and on the readiness of competitors and trading partners to accept infant industry protection on the other hand. Formal international trade disputes may be good indicators of the end of the emergence phase and instruments to restrict governments to more subtle forms of industrial support.

By the end of the special initial phase, firms in the industry need to have learnt not only to produce but also to compete by innovating. This learning process takes place within the realm of an emerging sectoral innovation system, which faces challenges such as: (a) bringing together and ensuring a sustainable supply of inputs, including physical capital and human capital, the technological base; (b) organizing learning and search directions for further technology and (c) fostering interactions (d) devising appropriate institutions, given the historical context and conditions of demand and competition. Development of the innovation system shall be discussed later in this section.

(2) Sustained competitiveness in an industry with a leading competitive segment

After the emergent phase, the industry may develop a sustained leading competitive segment. In 2000, both Japan, the producer of aircraft parts and components (including those made of composite materials) and Brazil, the assembler of regional jets (mostly from parts made elsewhere) had a value added in aerospace production of around 2.5 billion dollars (see Figure 2). In their own segments, both countries were highly competitive, yet these segments are vertically dependent on one another. Both require a complex, but different set of technological capabilities which their firms had evidently mastered. Thus it matters less which specific segment of the industry a country produces in, more how successfully it does so. What matters is the degree of competitiveness. A competitive industry is characterized by competitive prices, meeting international quality standards, increasing production and growing shares in global markets.

Competitiveness in a technology intensive industry is understood as more than merely having a static competitive edge based on factor endowments such as low wages. In a dynamic perspective, it refers to increasing value added per person while wages rise, diversification into more complex activities and increasing technological and organizational capabilities (Lall and Mortimore, 2005:3).

Given the fact that no aerospace producer has achieved market success without some form of government intervention thus national sectors compete (in various market segments) with each other, not only single firms. Thus shifting from an emergent to a competitive phase may require the reconfiguration of both company strategies and the role of the government. It does not necessarily mean a complete withdrawal of government intervention, rather it implies that protectionist policies and inward looking import substitution policies (that were deemed acceptable on the part of a newly industrializing country) are replaced by more subtle forms of support. This is also imposed by competitor firms and countries. International trade disputes are good indicators of competitiveness in aerospace industries as they refer to a country’s success.
as acknowledged by its competitors. The outcomes of these debates also shape the “norm” of what is an acceptable degree of intervention in the international community.\textsuperscript{6} Competitiveness has to be supported by a well-functioning sectoral innovation system, characterised by dense and multidimensional interactions among actors (including market- as well as non-market interactions through formal and informal knowledge channels). If competitiveness is understood in the dynamic sense, the innovation system should be able to respond to (and spur) changes in demand and to be able to supply leading firms with an adequate knowledge base to compete successfully on the market.

\textit{(3) Industry with no competitive products}

It is not inevitable that the emergent phase of an industry is always followed by a sustained competitive phase. The competitive state of the industry described in the previous section can be contrasted with a situation where no segment of the industry can supply competitive products in its market, although firms are pursuing productive activities. The reason for lack of competitiveness stems from inadequate technological capabilities of producers or is due to other barriers such as political ones. The corresponding sectoral innovation system is not functioning well. Linkages among actors may exist but innovative performance falls short of producers’ requirements. The products are complex but not able to satisfy market demand. Actors are unable to efficiently build the required knowledge base and mobilise innovation system input factors, the linkages and channels for knowledge flow are not operating adequately. Lack of competitiveness results in an over-reliance on government support (often military), while lack of interactions result in the sector falling behind the technology frontier. Institutional change is required to move out of this state of stagnation or falling behind.

In sum, the successful establishment of the aerospace industry in a latecomer economy depends on the shift from the emerging phase to a phase of sustained competitiveness. The strategic challenge in the development of the industry is sustaining innovativeness and offer products for the market that can gradually reduce the need for involvement of the government.

\textsuperscript{6} For greater details on international trade disputes of aircraft manufacturers, see Pavcnik (2002) or Goldstein and McGuire (2004).
3. A conceptual framework of interrupted innovation

3.1. Sectoral innovation systems
The competitiveness of a sector is closely related to the performance of its sectoral innovation system (Mowery and Nelson, 1999, Malerba, 2002). From a dynamic perspective, the competitiveness of a productive sector depends on its firms’ ability to accumulate technological capabilities in a changing environment to increase their value added. To differing degrees, firms learn how to respond to demand, how to produce. While doing so, their capabilities co-evolve with the scientific and technological knowledge frontier and with the institutions that regulate access and appropriation of such knowledge, as well as production and trade regimes. This co-evolution is apparent in the interactions between firm and other organizations and institutions. Such processes have been found to differ across sectors (Malerba, 2002).

In accordance with Malerba’s definition of a sectoral production and innovation system (2002), the aerospace industry is defined by its products, actors (firms and non-firm organizations), a scientific and technological (S&T) knowledge base and inputs, interactions amongst the actors and institutions. Delimitation of the boundaries of the innovation system is always difficult because the borders of science and technology domains are blurry and are constantly changing. However, for analyzing latecomers, drawing the boundaries of technology is less problematic than drawing national boundaries, because a large share of technology and input sources into innovation originates from abroad. Drawing the boundaries of the industry is similarly difficult. The most practical way is to take the final products to delimit the industry and include everything that leads to their innovation within the sectoral innovation system.

A sectoral system of innovation provides the source of technological change for an industry. (These sources may include a blueprint of a new product, any modification to an existing blueprint, a new way of production or organizing industrial activity. They may come from an R&D department designed explicitly to generate innovations but also from other employees as well as users of the industry’s products.) With its information and knowledge exchange, financial transactions, the innovation system is assumed to be closely connected to the production activities of the industry. These relationships, as well as those defining the relationship between firm, organizational and individual actors within an innovation system adhere to a set of rules, considered as the institutions. For the systems to function, these rules need to be clearly defined and acted upon, which also means that the innovation system – or at least its core – remains unchanged over a certain period. However, from time to time, components of the system, including actors, their capabilities as well as the institutions defining their relationships will change. The framework we shall present below intends to shed more light on these changes.

3.2. Innovation systems in motion
Analysis of the emergence and dynamics of an industry also implies the analysis of the corresponding emergence and dynamics of the sectoral innovation system. However, studies rarely make this relationship explicit, leaving the dynamics of innovation systems under-researched. There are especially large gaps in our knowledge concerning the case of developing countries.

7 Aircraft, spacecraft their engines and propulsion units and parts and components. The focus of this paper is primarily on the aircraft segment.
8 As Lundvall recently noted: “Notwithstanding the clear links between innovation system research and evolutionary economics, understanding the dynamics of different innovation systems and different
From the very origins of the concept, innovation systems have conceptually been associated with socio-economic change. With the increasing availability of longitudinal data on innovative performance of interrelated actors, there is increased interest in understanding how systems undergo significant change over time, both in qualitative and quantitative terms (Lundvall et al., 2006; Dodgson et al., 2008). Fundamental changes in the economy as a result of creative destruction (Schumpeter, 1934) or the emergence of new technological paradigms (Dosi, 1982; Freeman and Perez, 1988) have been widely discussed. These theoretical works focus on an aggregate level. We still need to expand our understanding of the co-evolution of science and technology, innovation and production and the relevant institutional arrangements. In other words, how changes in the innovation system are connected to changes in a sector’s physical production.

The evolutionary aspects of innovation systems have received increased attention in recent years. Three distinct patterns of system change are crystallizing from these works, irrespective of whether the analysis focuses on the national, sectoral or technological level. The first type of work refers to incremental changes along a given trajectory (bounded by path dependence). The study of the Taiwanese integrated circuit industry by Lee and von Tunzelmann (2005) provides useful insights into this type of dynamics, in which the interplay of sub-systems and major actors are at the core of a more gradual system change.

The second type of innovation system change refers to a more fundamental or structural transition. The ‘appreciative theorizing’ model of Galli and Teubal (1997) originates paradigmatic changes and structural adjustments of NISs in exogenous environmental pressure. The change involves restructuring networks, changing openness to the outside world, increased interactions between the subsystems (i.e. inter-firm relations evolve beyond simple market-based transactions), and the creation of new technology interface units. Lundvall et al. (2006) single out the institutional set-up as the key barrier to growth of a NIS after a certain point. A system transition is required to overcome the case of contingency mismatch (when change in the environment makes the existing institutional set-up ill-suited) or when a system reaches its inherent limits as a result of endogenous economic growth.

Instead of looking at system structure to analyze change, a new strand of literature has emerged focusing on the functional dynamics of (mainly technology-specific) innovation systems (Hekkert et al. 2007, Bergek et al. 2008, Edquist and Hommen 2008 and Liu and White). In this heuristic approach, the evolution of a complex entity, such as an innovation system can be understood as the evolution of its functions (entrepreneurial activities, knowledge development and diffusion, guidance of the search activities, market formation, resource mobilization and creation of legitimacy, following the taxonomy of Hekkert et al. (2007))

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10 New in the sense that these studies are focusing explicitly on identifying the different functions of a system (or any changes in those functions). The analysis of crucial processes in the system were already present in the early works on NISs (e.g. Nelson 1993) but Galli and Teubal (1997) also discussed hard and soft functions in the context of the changing role of organizations.

11 For a good overview of the differences in taxonomies, see Table on p.426 of Bergek et al., 2008.
evolution of a system but could originate from outside the system. ‘Systemic innovation’ (or changes in the system) results from the fulfillment of functions that positively influence each other and bring about creative destruction. Conversely, negative fulfillment a function spills over to another eventually slowing down or stopping progress (Hekker et al., ibid). The role of institutions differs from the previous two ‘structuralist’ approaches since they only gain meaning related to a functional domain. Thus, no matter what the point of entry is to analyze system change, institutions have been found crucial for the performance as well as the transformation of a system.

The management literature offers interesting insights as well. The concept of architectural innovation, introduced by Henderson and Clark (1990) originally refers to changes on the product level in the way the main components are linked together. Consider the product design architecture as a simple system, a structural change of the linkages of the system that offers a competitive edge to a firm is analogous to architectural innovation in a national or sectoral innovation system.

Due to its cyclical nature, the aerospace industry offers an interesting field of investigation. Recurrent booms and slumps in demand regularly pose challenges to innovation and production. It is reasonable to assume that not only firms, but the system as a whole is affected by demand fluctuations. The industry’s performance depends on how the innovation system as a whole manages to cope with these fluctuations. Analyzing dynamics of the system requires a careful look at its elements. A central problem with quantitative analysis is often the lack of detailed long-term data. Nevertheless, change in inputs, demand and output; changes in the number of actors or changes in the intensity of interactions (network characteristics) are indicative of the dynamics on innovation system.

3.3. Institutions

Qualitative analysis is required to highlight changes in the knowledge base and learning processes; changes in the nature of interactions among actors (including change network hub change); institutional change; changing processes of variety generation and selection.

Innovation system change requires a comprehensive analysis of the above factors, with constantly contrasting changes with the effects on physical output, productivity or competitiveness of the sector and its effect on the pace of convergence. Institutional changes play a central role. (Although the distinction of institutions and organizations are often confusing in the innovation systems literature, institutions are understood here in the sense of North, as “the rules of the game in a society or more formally ... the humanly devised constraints that shape human interactions”. (North, 1990)) Coriat and Weinstein (2004) argue that for innovation, the following institutions are the most relevant: institutions providing/regulating the appropriability of science and the technological knowledge base (a basic input for innovation); institutions concerning the financing of innovation, the educational system, national labor laws and capital-labor arrangements. For the purposes of our sectoral focus, we would complement this list with institutions that provide rules and norms for inter- and intra-industry trade relations concerning not only knowledge and labor, but the flow of goods as well. Access to technology embedded in machines has proven to be crucial for latecomer entrants.
3.4. Systems transition
Innovation system dynamics include changes within as well as changes of a system. Despite the fact that this latter has the potential to alter the innovativeness of the system more significantly, it is often hard to make a clear distinction between the two due to the co-evolutionary processes of industrial development. Larger, qualitative changes of [the nature of] the system originate from institutional change that creates a new type of network among the actors. Following Lundvall et al (2006), we shall refer to changes in the “constellation of institutions” and changes “in the relationship between producers and users of knowledge” as ‘transitions’. In a different way, this is discussed in the multi-level framework proposed by Geels and Kemp (2006) where transitions are shifts between technological trajectories, involving a radical innovation incubated in a ‘technological niche’.

3.5. The main components of the framework
The size of an innovation system is defined by the input resources into innovation and technological change (investment in R&D, human capital engaged in the development of new products and processes or organizational change as well as marketing or economically applicable knowledge). The literature does not provide a clear definition of the performance of an innovation system or provide simple ways to measure it. We refer to the performance as the economically applicable instruments (new products, processes, organizational forms, resources, etc.) that induce technological change. Many of its aspects are rather difficult to measure; indicators such as the number of new product designs, the share of new products in sales, number of patents, citations, trademarks may be used to characterize performance.

The maximum innovative performance a sectoral system can reach with a given combination of inputs under an institutional structure defines the performance frontier of the system. [*Need to stress similarity to production function?* diminishing returns to scale]
By supplying the system with additional units of resources (elements of a given set of resource types), the innovation performance increases (the more resources available for a national-sectoral innovation system, the more outputs it will provide). But within the constraints of a given innovation system, performance is constrained by diminishing returns – similar to a production function.\(^\text{12}\) It is also conceivable that after a certain point performance will start to decrease since the larger the size of the system, the more complex it becomes, and the more costly it will be to coordinate the use of resources.

We make an attempt below to visualize the relationship between size and performance of a sectoral innovation system and the effect of institutional change. At this point, the illustrations are to be seen as a metaphor, given that accurate measurement of the system is not yet provided.

The graphical illustration of an innovation system’s performance in Figure 3 shows the evolution of the performance frontier curve \(p\) as the innovation system size (resources available for innovation) increases. There is no reason to assume that the sectoral innovation system in any country performs at the maximum of its potential capacity. As it has been often shown since Nelson and Winter (1982), “producing” innovation is far from being straight-forward. It requires immense tacit and codified knowledge, agents

\(^{12}\) Modern growth theory (Lucas, Romer etc) states that there are no diminishing returns to increasing knowledge inputs. We argue that this view needs to be modified. Increasing inputs into a given static system of innovation are subject to diminishing returns. Only if the innovation system succeeds in continuously reinventing itself and changing its nature dynamically will diminishing returns be overcome. This requires a kind of transitions from one innovation system to another.
do not make choices based on perfect information and whether the effort brings successful outcome is rather uncertain. How close a country performs relative to the frontier thus depends in a major part on the knowledge accumulated in the industry. In a simplified way, a country’s vertical movement from point A to B on the graph corresponds to increased intensity of interactions among actors that yield higher performance. At the end of the day, it shows the system’s success in learning the art of innovation (within the constraints of the scope determined by the set of resources). (This of course takes time, which will be discussed below.)

Figure 3 Performance in a given innovation system

3.5. Movement of the innovation system frontier
The performance frontier can shift as a result of two kinds of change. The first one refers to smaller adjustments to the setup of the innovation system (small, often iterative improvements concerning the nature of interactions within a system, possibly as a result of innovations originating from the system but can also be external) that influences the performance. As shown in Figure 4, this can be illustrated with a relatively small vertical shift of the performance frontier curve (from $p$ to $p'$). The main feature of such an incremental change is that the core resources and key institutions of the sectoral system remain essentially the same.
A more radical shift of the system is caused by a more fundamental, qualitative change in its constitution. The entry of new actors carrying new capabilities that affect existing relations, a significant change in the technological base that the system draws upon, and, crucially, a change of institutions are expected to trigger this second kind of shift. Figure 5 shows this qualitative change by the transition from performance frontier curve I to II. Such a shift to a higher performance frontier curve will not only allow an industry increased competitiveness, but given the diminishing returns, is the only source of competitiveness gain after a certain size. This is a major force that drives radical shifts from time to time.

The aim of any competitive industry is to continue to increase its innovative performance, in other words, attempt to shift the innovation system upward. Nevertheless, theoretically, it is similarly conceivable that for certain reasons the performance of the new system will turn out to be inferior to the previous one. For in the end, if institutional memory is erased due to shocks, the establishment of a new system based on new combination of resources and new institutions is an uncertain and risky process. Should this be the case, actors are expected to recognize this and make an attempt to reconfigure the system but only if institutions permit them to do so.
There are a number of empirical issues of innovation system dynamics this simple model can illustrate; it is for historical evidence on industrial development to reveal for instance how regularly these shifts occur, what triggers them or what the direction of changes happened to be.

### 3.6. Changes in a national-sectoral innovation system: learning trajectories

These graphs also allow us to plot how the sectoral innovation system in one country changed size and performance over time. The trajectory of a country will be indicative of the way institutions function and is a tool to reveal major constraints to or opportunities of industrial competitiveness that have to do with the (in)efficiency of the innovation system. Let’s consider a latecomer industrializer for an example (Figure 6).

As resources available for the sectoral innovation system increases, its actors learn to utilize the institutional setup to reach near-frontier performance with their interactions, so will the system move higher and closer to the frontier (movement over time from $T_1$ to $T_3$). What happens when the system reaches the frontier? Assuming that its aim is to increase performance, staying on the frontier that converges to zero (and then presumably negative) growth will marshal the forces of change in the institutions. If the change takes place in a short time, the sectoral system can jump to a new growth path without significant performance loss and any further increase will be relative to the new performance frontier. Otherwise, and we expect this to be a rather likely case when it comes to an industry prone to huge drop in demand, the innovation system’s performance shrinks and an interruption occurs. This is illustrated by the movement from $T_3$ to $T_4$ in Figure 6. (Note that temporary decrease of the performance of the innovation system should not immediately affect the output of the industry; nevertheless, drop in the output of the industry may result in shrinking resources available for innovative activities.) An interruption will necessary take place because the old institutions have to be ‘dismantled’ before the new ones become effective. In case of a latecomer country, should this drop be too big and chances to collect resources for a recovery too dim, the interruption may well offer a moment to abandon further efforts to develop this particular industry.
Recovery after an interruption is not expected to show higher performance even in case a successful transition occurred. Increased performance is only shown with time, considering that once again, the actors need to learn how to achieve maximum performance with relation to the new frontier (should this frontier be superior to the previous one). Figure 7 shows a successful transition to a new system defined by frontier curve II. Notice that at point $T_5$ in time, the new system will not perform better than the old one and the increase will only become apparent at point $T_6$.

When we plot innovation system performance of one country over time, rather than against size as in the previous graphs, the development trajectory is expected to take the form of a set of S-curves. The reason for this is that the industry follows a learning
curve in its attempt to converge to frontier performance. That is, up to the point of interruption. Interruption occurs with an abrupt fall of performance at a short period of time. It is the crucial task for the relevant actors to react to the crisis by reconfiguring the institutions in an innovation system and possibly expanding it with new resources. This is done in order to direct learning efforts on a trajectory that allows the supply of innovations required by the changed demand conditions the industry faces. The sectoral system is then attempting to converge to a new frontier (expected to exceed the performance of the previous one) and hence a new S-curve rises from the point of system change. The distance in time between the point of interruption and that of system change depends on the readiness and capability of the actors to react to changes in the environment, and is thus a measure of flexibility of the industry to change the innovation system. Figure 8 follows the learning trajectory (L) of the country in Figure 7 before \( T_{1,3} \), during \( (T_{3,4}) \) and after \( (T_{4,6}) \) the successful transition from performance frontier curve \( I \) to \( II \).

**Figure 8 A learning trajectory: interruption and transition**

![Learning trajectory diagram](image)

Figure shows a country’s learning trajectory, including the transition between innovation systems at points of interruption. 
\( T_1 \rightarrow T_2 \) interruption 
\( T_3 \rightarrow T_4 \) recovery after interruption 
\( T_5 \rightarrow T_6 \) successful shift to trajectory \( L^{II} \)

### 3.7. System performance and competitiveness

Long-run competitiveness of a high-tech industry depends on the capacity of its sectoral innovation system to provide cost-cutting and productivity-increasing innovations and products with technological features superior to the competitors.

How does competition feature in our framework?

Competition is a key driver behind innovation system performance increase (or upward movement). Suppose that industries from two different countries compete while supplying the same market face similar frontier curves. The one that is closer to the frontier has a higher propensity to innovate, hence a higher chance to be more competitive. That is, if the performance frontier curves are similar. However, since national institutions play a central role in the system performance, countries not only compete in their relative distance from the frontier, but also in the position of the frontier (performance frontier curves of different countries would look differently even if they produce for the same market). They will then aim at increasing competitiveness...
by moving closer to the achievable performance frontier and shift the frontier further out. This implies two kinds of costs. First, the learning costs associated with narrowing the distance to the frontier; and second, the transition costs. These costs are borne by the entire innovation and production system. Only if the industry is producing competitive products can these costs be recovered. A key dilemma for system governance is to find the most cost-efficient way to manage system transitions. Incremental change will not bring about as great gains as radical ones, but the cost of institutional change is higher. Path dependence, the comfort of established routines, the lack of information on the alternatives, the uncertainty concerning outcomes of institutional change reduces the likelihood of the occurrence of major institutional changes.

Is there still a way to compare innovation system performance? We argue that comparing innovation input and output indicators are only meaningful to the extent that the changing institutional context is duly taken into account. Good indicators of system-level performance are sales performance (including domestic and export markets) and market shares of final products.

Finally, there is another element of competitiveness: the speed of reaction to a global drop of demand for products, in case of crises. Competitiveness in these instances is measured by the flexibility of the industry, or its ability to respond timely to the changing demand conditions by changing institutions. McKelvey et al (2006a,b) discuss rigidity and flexibility of innovation systems and identify the period of adjustment to new demand conditions (both external and internal to the industry) critical moments. Also at firm level, Yuan et al (2010) showed that strategic flexibility matters; it is reasonable to assume that a first movers’ advantage exists when it comes to competition of industries. The one that is set on the new path first has the highest likelihood to recover from the depth of an interruption.

3.8. Questions for case studies

Based on this conceptual framework, there are a number of potential questions to investigate in the historical evidence of industrial development.

First, what did the latecomer development trajectories look like? What caused interruptions in the development of the sectoral innovation system and what characterized the transition period? When was a transition period successful and who governed the transition?

On a more general level, when can we talk about the end of the emergence phase, and can it be associated with interruptions and transitions?

A crucial difference between established (or mature, see Chaminade and Vang, 2008) and emerging innovation systems is that emerging ones are more vulnerable to external shocks. These shocks can cause interruptions where previously acquired technological capabilities are lost. Even leading producers have found to be prone to ‘organizational forgetting’. This phenomenon is expected to affect emerging countries with weaker institutions even harder. How did interruptions and transitions affect the accumulation of latecomers’ technological capabilities? (Or, how can ‘transition-institutions’ minimize the effect of interruption causing erosion of capabilities in an innovation system?)

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13 There is a large number of studies measuring national innovation systems in their institutional context (Godinho et al, 2003; Hollanders . . . ) and, mostly for technology-based systems based on how well they perform certain functions (Carlsson et al 2002, Bergek et al 2008).

14 Production experience can depreciate, not only appreciate over time (Benkard, 2000)
4. Crises and system dynamics: Examples of system change from case studies of aircraft industry

Times of crisis offer ideal points of entry observe innovation system change. The drop in demand puts both the production and the innovation system to a test. Since it jeopardizes survival, it triggers responses from the system. As pointed out earlier, crises are cyclically returning challenges in the aerospace industry, and stakeholders need to be prepared for slumps and need to learn how to respond and find innovative solutions to weather the crises and set the industry on a growth path more rapidly than its competitors.

In this section we present cases where crises triggered size changes of sectoral innovation systems of aerospace, in the case of two countries, Brazil and China.

BRAZIL

In 1969 a state-owned enterprise, Embraer was established by a presidential decree to produce and market commercial aircraft. By 1980 the company has grown to nearly 6000 employees and has manufactured over 300 of a locally designed 15-19-seater twin-turboprop aircraft, the Bandeirante, more than 400 of a single-seater agricultural piston plane, the Ipanema, and launched the pressurized executive twin-prop, the Xingu. In 1981, the company earned some 190 million US dollars from exports, and nearly 440 million dollars from sales (Figure 9), and made a profit of 26.5 million dollars.

**Figure 9** Embraer’s sales, exports and number of employees, 1970-2007.
(Values in millions of constant = 2000 USD)


15 The case of Brazil and the history of Embraer has been widely discussed in the innovation systems context (to highlight but a few studies, c.f. Cassiolato et al 2002, Marques 2004, Marques and Oliveira 2009).

16 Figures are from Ramamurti (1987); values adjusted to constant 2000 US dollars.
4.1. Slow transition from military to commercial production

The successful launch of Embraer marks the end of a transition period. The Brazilian aircraft industry was in a crisis after the Second World War. During the war Brazilian factories produced hundreds of small military trainers for the Allies (Figure 10). By the end of the 1940s the competition of technologically more advanced US producers drove the four local aircraft factories\(^\text{17}\) out of business. Why did it take over 20 years before a new company could emerge from the ruins?

Figure 10 Aircraft production in Brazil

![Aircraft Production in Brazil](image)

*Source: Vertesy and Szirmai (2010, Fig 1, p.2.)*

First, there was a lack of overarching strategy on how to develop the sector. It was clear that Brazilian firms did not possess the capabilities to produce what was locally demanded. Previous experience in producing small, propeller-driven planes was insufficient to meet the demand of commercial aviation for larger planes to serve transcontinental routes and smaller passenger planes to provide access to the vast inland areas of Brazil with poor airport infrastructure. The military needed planes to provide effective control of the country’s airspace and train pilots. The provision of trainers was easier to meet making use of existing capabilities. However, the benefit of local production over importing planes from more efficient and thus cheaper suppliers was debatable. The sheer size of investment required for educating and training the required human capital, for machinery and equipment, or to develop new designs explains partly why the government was hesitant in outlining any strategy and appropriating large sums in the budget. Nevertheless, the establishment of the Technology Institute of Aeronautics (ITA) and the Aerospace Technical Center (CTA) or the procurement of a team of German aeronautical engineers in the early 1950s indicated the government’s dedication to maintain and improve technological capabilities in the field of

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\(^{17}\) The four companies were The National Air Navigation Company (CNNA), Companhia Aeronautica Paulista (CAP), Fabrica de Galeao and Fabrica de Avioes de Lagoa Santa.
aeronautics\textsuperscript{18} and pleased those lobbying for a grand strategy to develop the industry (among them industrialists in the states of Sao Paulo and Rio de Janeiro, and officers, pilots and aircraft engineers from the Brazilian Air Force (FAB)). Second, the accumulation of technological capabilities always takes time. The constant flow of graduates from ITA as well as the arrival of experienced European aircraft designers\textsuperscript{19} with new ideas contributed to increased experimentation with small aircraft designs mainly at CTA’s R&D department (IPD) and at a very few private enterprises. However, aircraft design remained a small-scale activity, relying mostly on limited military orders. Production and maintenance activities could only keep two private light-plane producers in business, Aerotec (a spin-off of CTA) and Neiva. Producers did not take part in global competition and remained well behind the technology frontier in their market segment. Capabilities were still not in line with the market demand. General aviation was insufficient to provide an opportunity for producers to learn to compete. Access to technology was limited to what was public knowledge (through linkages with foreign universities and research institutes) or “embodied” in skilled individuals (foreign aircraft designers).

In short, during the 1950s and 60s the basic tenets of a sectoral innovation system were established. The emergence of its main actors and linkages happened slowly and without a clear central mission. But for a sectoral innovation system to reform and provide the impetus for industrial growth and catch-up, the emergence of an entrepreneur or innovation system broker was essential.

The system brokers were Ozires Silva\textsuperscript{20} and his team at CTA who played a central role in (1) finding a market niche (commuter aircraft capable of serving airports with poor infrastructure) and (2) channeled finance and design efforts to successfully develop a new product for this niche (IPD-6504); (3) established a company to ensure commercial valorisation of innovations (Embraer, 1969). (4) New linkages were created to provide capital (government launch support, commissioning 80 Bandeirantes and subsequently new planes, and a corporate tax incentive scheme channelling private capital to Embraer) and technology (through an exclusive contract with Piper or a deal with Italian producer Aermacchi, an offset contract with Northrop and collaboration with the Canadian engine manufacturer Pratt & Whitney).\textsuperscript{21}

The empirical evidence of successful system transition is ample. On the output side, Figure 10 shows the production cycles of major new products: the EMB-110 Bandeirante 19-seat commuter plane, the EMB-312 Tucano (single-engine military basic trainer), the EMB-121 Xingu (a pressurized executive twin-turboprop), and the EMB-120 Brasilia (a pressurized 30-seater twin-turboprop commuter). Figure X shows the increase of sales revenues of Embraer (to a historical maximum of 924 million USD in 1989) and the growth of exports (nearly two-third of sales revenues by mid-1980s; growing to 486 million USD in 1989). This shows that Embraer’s strategy of aiming at

\textsuperscript{18} ITA not only provided a constantly growing, well-trained stock of aerospace engineers and technicians, but also maintained active linkages with leading foreign technical institutes, ever since MIT faculty assisted its establishment.

\textsuperscript{19} Foreign designers included Heinrich Focke, who collaborated with CTA; Willibald Weber and Joseph Kovacs who worked with the industrialist Jose Carlos Neiva; or Max Holste, who helped design the first commercial plane for CTA, that became the Embraer Bandeirante.

\textsuperscript{20} An air force pilot, ITA (and later Caltech) graduate aeronautical engineer, founder and president of Embraer (1969-86), who also played a key role in its privatization in 1994.

\textsuperscript{21} (Due to space limitations, we refrain from presenting the history in greater details, but there is an extensive literature to cover these points: Silva, 2002, Cabral, 1987, Ramamurti, 1987, Frischtak, 1992, Cassiolato 2002, Embraer.)
the commercial commuter market\textsuperscript{22} paid off, especially after the liberalization of the US market (in 1981, Bandeirante had a 37.8% share in the 15-19 seat segment\textsuperscript{23}). Brazilian aerospace value added grew to 220 million by 1980 and 790 million USD by 1989. This growth is especially remarkable contrasted to the global industrial landscape, shaken by the oil crisis. The Brazilian growth during the 1970s was nearly 10-times the growth of the global industry (capitalist economies). Even after the start-up decade, the 258% growth between 1981 and 1989 still overshadows the global average of 122% (and 125% of the USA), providing a clear evidence of catch-up (Figures 11).

\textbf{Figure 11} Trends of catch-up: aerospace value added of Brazil, China and Indonesia compared to the US, 1970-2007 (%)

Sources: Chinese National Bureau of Statistics, IBGE, UNIDO.

We argue here that the emergence of the innovation system and its institutional set-up was a necessary precondition for the accelerated growth of the industry. We do not debate the crucial role of Embraer’s management in successful formulating and execution a sound strategy for the increased sales performance and growth. However, the creation and channelling of resources external to the company and the establishment of the general institutional arrangement for innovation and production, as well as the performance of the dominant company were all interacting in a systemic manner. The main elements included skilled labour available (and affordable) locally, the presence of R&D activities (and results which Embraer commercialized), the openness to foreign technological sources, the military procurement for new aircraft development and the subsequent financial arrangements, or the protectionist trade policies of the government. The establishment of Embraer as a state-owned enterprise\textsuperscript{24} was the final institutional innovation in the formative phase of the SIS. A national champion allowed to reap the benefits of an already existing SIS and to set the forces of innovation in motion. It was a necessary condition for the increase of innovative performance, since much of the tacit knowledge required for competitive production based on up-to-date technology needed to be acquired through ‘learning by doing’.

\textsuperscript{22} Already at the development of the Bandeirante, US FAA guidelines were fully observed to facilitate certification, which is essential for exports. Airworthiness certificate was given by France in 1977, by the UK and the US in 1978. Feedback from regional airlines and other users was considered seriously for the development of subsequent models.

\textsuperscript{23} Sarathy, 1985

\textsuperscript{24} State ownership was a last resort to overcome the lack of private venture capital (Silva, 2002)
State ownership did not preclude Embraer management to govern certain functions of the innovation system. The successful emergence of the Embraer-championed aircraft industry in Brazil – what Ramamurti (ibid) aptly refers to as a combination of public power and private initiative – was in fact the result of shared governance of the innovation system. Certain functions (following the typology of Hekkert et al, 2007), such as ‘knowledge development’, ‘knowledge diffusion’ were shared between CTA and Embraer’s R&D departments or foreign sources. ‘Guidance of search’ for new technologies and ‘market formation’ were jointly influenced by the marketing strategy of Embraer and the procurement policies of the Air Force or the Aeronautical Ministry. The government played a more decisive role (especially at the beginning) in ‘resource mobilization’ (including capital, skilled labour and technology), Embraer (and other smaller companies) provided ‘entrepreneurial activities’ for the system.

This governing structure remained in place until the next major transition of the SIS. Over the years as production increased smaller adjustments or iterations were made in the institutional framework (often to meet the needs of Embraer). This indicates a gradual ‘co-evolution’ of technology, institutions and organizations. However, the performance of the innovation system increased and so did its size, without any significant trend brake.

### 4.2. The Crisis

The period 1990-94 marks the second crisis of the Brazilian aircraft industry. While global recession caused value added for the global aerospace industry to decline by 30%, Brazil was hit more severely by a 70% drop. Sales plummeted by some 75% and export by 80% from the level of 1990. Figure 10 reveals not only the reduced production of the EMB-120 Brazilia, but also a gap where no new aircraft was introduced to the market. This therefore indicates a crisis of the innovation system. The primary cause of the crisis was a daunting lack of financial resources. The preceding years saw the end of the military dictatorship and a financial and economic crisis in Brazil. The previous practice of financing new product development with government launch support was not an option anymore. Financing R&D for a new regional turboprop plane by own resources was beyond the capacity of the heavily indebted Embraer, and collaboration with the Argentinean FAMA turned out to be too costly. By 1994 R&D expenditures of Embraer exceeded 30% of its sales. (Figure 10). The company had to reduce its workforce to less than half of the 1989 levels.

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The survival of the production and innovation system was at stake, and more than 40% drop in foreign companies’ patenting marks a significant lack of trust in the SIS (Figure 13). Although patents are less appropriate measure of innovativeness in the aerospace industry, the trend of foreign companies patenting in Brazil is a crude indicator of technology flows and technological learning in the innovation system. Given a strict intellectual property regime, foreigner’s patenting activity reflects their estimation of local technological capabilities. During the 1980s nearly 40 patents a year were added to the stock (Figure 13), followed by a sharp, four-year interruption.

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26 Patents are less meaningful indicators in the aerospace industry as compared to other high-tech industries such as biotech, since innovations are preferred to be protected by secrecy (Niosi and Zhegu, 2005), which is a rather efficient way given the high capital barriers.

27 We distinguished patents in aerospace (classification B64) filed at the Brazilian patent office by the nationality of applicants. The two groups are: all-foreign, where there is no Brazilian applicant, and the rest, where there is at least one Brazilian applicant. Note that change in the trend can also be caused by an overall change in innovative performance of foreign firms.
By that time, the technological challenges of aircraft manufacturing changed from priorities of economy and fuel efficiency to cost, noise and capacity (Sehra and Whitlow, 2004). The global industry had already introduced new ways to cut costs. These included the geographical expansion of supply chains and sharing development costs with component manufacturers, and the development of aircraft families of high commonality between models. Embraer still vertically integrated all design and production phases and performed R&D activities in too many different directions (Frischtak 1992). The Brazilian industry lost its competitive edge and the innovation system was not sustainable to help regain it.

4.3. Innovation system transition and result

The solution was a change in ownership that fundamentally altered the sectoral innovation system. In 1994 Embraer was privatized to a consortium of domestic investors. Although the government did not use military procurement for launch support, it continued to fund part of Embraer’s R&D activities and exports28 (through FINEP, BNDES and Banco do Brasil). At the same time, spin-off enterprises (with former Embraer employees) joined the local supplier chain. Privatization resulted in capital injection as well as in greater flexibility to sign partnership agreements to jointly develop a family of regional jets. Risk-sharing partnerships (see Figueiredo et al, 2008) reduced R&D costs for Embraer and became an important new technology source. Embraer changed redefined its core competence as aircraft designer and system assembler.

The results of these institutional changes are highly remarkable. Between 1994 and 2000 sales rose on the wings of the ERJ-145 regional jet family from less than 200 million to over 2.8 billion US dollars, more than 97% of which came from exports; value added increased to 2.3 billion USD (Figure 14). At the same time while Embraer’s R&D expenditures increased, R&D/Sales decreased from over 30% to less than 5% (Figure 12) although Embraer was developing the larger E-170-190 family, accommodating up to 120 passengers, becoming a direct competitor of the smallest Airbus and Boeing models. Embraer introduced over a dozen new models of regional and executive jets since the system transition and became third largest manufacturer of jet aircraft worldwide in terms of delivery.

28 The PROEX export financing scheme was contested in a WTO trade dispute by Canada, but after the settlement a slightly modified version still remains in place (see Goldstein and McGuire, 2004).
4.4. A new transition?

Companies in the Brazilian supply chain benefited from the growth during the late 1990s, however, as the number of risk sharing partners decreased and so did the Brazilian content, value added fell back to 2 billion USD.\(^{29}\) There are several signs of shortcomings of the SIS that may signal some further changes, albeit less fundamental than those in the 1950-60s or in 1994.

The Brazilian aerospace industry recovered from the post-9/11 demand shock relatively rapidly. However, the crisis of 2008-09 showed greater vulnerability of an industry dependent on regional and executive jets. The relatively outdated technological capabilities, the lack of sufficient credit lines and venture capital make it difficult for local SMEs to become competitive (such as risk sharing partners) in global supply chains (ABDI, 2009). To boost the competitiveness of local SMEs is a major concern for the government. There is a growing local consensus for the need to modernize the education and training system, to support innovativeness through new missions, procurement policies or offset agreements targeting the supplier chain to create a globally competitive center of excellence in aerospace.\(^{30}\) As a first response, in 2009 the government officially commissioned Embraer to develop a military transport and tanker aircraft (the K/C-390).

In the meantime, the global industry needs to answer a new set of technological challenges, including even more economic performance and lower greenhouse gas emissions. Latest large civilian aircraft designs use composite materials at an unprecedented scale, in which Embraer is lagging behind. In the regional aircraft market new players (including Comac in China, the Russian Sukhoi and Mitsubishi in Japan) have made significant investments to break the Bombardier-Embraer duopoly. Thus the

\(^{29}\) For a discussion of trends in value added and labour productivity, see Vertesy and Szirmai (2010).

\(^{30}\) Clearly indicated by recent detailed, comprehensive studies, see ABDI (2009) and Montoro and Migon (2009).
competitiveness challenge calls for further growth in the performance of the Brazilian sectoral innovation system.

Our indicators show that once again an interruption has taken place in the growth of the innovation system following the global financial crisis. While the technological challenges and complexities are increasing, it is unlikely that private investment will flow into the sector similarly to the levels during the years of accelerated globalization in the late 1990s. The institutional changes once again suggest an increased government intervention (as do major competitors); national-sectoral innovation systems will thus be competing on who finds the most efficient, but also sustainable financing mechanisms.
Table: Major changes in Brazilian Aerospace Production and Innovation System

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<tbody>
<tr>
<td><strong>Production</strong></td>
<td>• Formation: mostly private industrialists’ investment</td>
<td>• Formation: Spin-offs from CTA (Embraer, Aerotec) or later from Embraer</td>
<td>• Formation: spin-off from Embraer; foreign partners establishing limited local activities</td>
</tr>
<tr>
<td></td>
<td>• Structure: vacuum after end of WWII orders</td>
<td>• Structure: SOE dominant position;</td>
<td>• Structure: dominant private giant; weak domestic supply chain</td>
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<tr>
<td></td>
<td></td>
<td>• SOE: Activities vertically integrated</td>
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<tr>
<td><strong>Main products, ‘core competence’</strong></td>
<td>• small planes for aero-clubs or military training</td>
<td>• turboprop commuter and light executive aircraft;</td>
<td>• regional jets, executive jets;</td>
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<td></td>
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<td>• military trainers;</td>
<td>• military trainers;</td>
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<tr>
<td></td>
<td></td>
<td>• small planes (general aviation, agriculture)</td>
<td>• agricultural planes</td>
</tr>
<tr>
<td><strong>Main markets</strong></td>
<td>• Domestic general aviation and low-end military</td>
<td>• foreign (USA, W-Eur, Latin-America) &amp; domestic commuter market and low-end military markets</td>
<td></td>
</tr>
<tr>
<td><strong>Source of growth</strong></td>
<td>• limited due to limited domestic market</td>
<td>• export-oriented growth</td>
<td>• exclusively export-driven</td>
</tr>
<tr>
<td><strong>Capital Source, Financing</strong></td>
<td>• limited private sources; government commissions</td>
<td>• government launch support;</td>
<td>• government export credits</td>
</tr>
<tr>
<td><strong>Labor Source</strong></td>
<td>• other heavily industries; locally trained engineers; air force</td>
<td>• sales revenues</td>
<td>• sales revenues</td>
</tr>
<tr>
<td><strong>Innovation</strong></td>
<td></td>
<td>• locally trained specialist engineers (ITA, in-house); blue-collar workers</td>
<td>• locally trained specialist engineers (ITA + in-house);</td>
</tr>
<tr>
<td><strong>Main actors</strong></td>
<td>• government-funded R&amp;D institutes;</td>
<td>• Embraer; foreign partners;</td>
<td>• Embraer;</td>
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<td></td>
<td></td>
<td>• Graduates of ITA</td>
<td>• Limited local firms</td>
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<td></td>
<td></td>
<td></td>
<td>• Graduates of ITA</td>
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<tr>
<td><strong>Major innovations</strong></td>
<td>• New small-plane designs; not marketed</td>
<td>• new commuter and executive aircraft; new military aircraft</td>
<td>• new regional and executive jets</td>
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<tr>
<td></td>
<td></td>
<td>• new production processes</td>
<td>• new design processes (with the use of ICT)</td>
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<tr>
<td></td>
<td></td>
<td>• expansion of global commuter and executive market</td>
<td>• expansion of global regional market</td>
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<tr>
<td><strong>Main source of knowledge:</strong></td>
<td>- Technology</td>
<td>• research &amp; development at CTA (IPD);</td>
<td>• codified knowledge through tech. licenses and joint ventures</td>
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<td></td>
<td></td>
<td></td>
<td>• in-house R&amp;D</td>
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<tr>
<td></td>
<td>- Human Capital (tacit knowledge)</td>
<td>• Other heavy industries;</td>
<td>• ITA-trained engineers; in-house training</td>
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<td></td>
<td></td>
<td>• air force pilots &amp; maintenance technicians</td>
<td>• Tacit knowledge through foreign assistance with licenses and joint ventures</td>
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<td></td>
<td>• Foreign designers’ tacit knowledge</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>• ITA-trained engineers</td>
<td></td>
</tr>
<tr>
<td><strong>Source of Finance</strong></td>
<td>• Government (Brazilian Air Force) new design commissions; limited private funds</td>
<td>• Government launch orders;</td>
<td>• Sales revenues;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Domestic firms through tax incentive scheme</td>
<td>• Risk sharing partners</td>
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<tr>
<td></td>
<td></td>
<td>• Sales revenues</td>
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<td></td>
<td></td>
<td></td>
<td>• Limited government funds</td>
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Main achievements. After entering the aircraft manufacturing industry in the 1950s, China has become a producer and – to a lesser extent – exporter of fighter jets (Figure 17), bombers and light transport aircraft during the Cold War (CIA 1972, Allen et al, 1995, Frankenstein and Gill, 1996). Since the 1990s firms of the Chinese aeronautical conglomerates have joined the global supply chains as manufacturer of commercial aircraft parts and components for western producers, including Airbus and Boeing (KPMG, 2004). In the last decade foreign manufactures (Embraer, Airbus) brought final assembly work to China and the Chinese company (Comac) designed and produced a prototype of a regional jet (Goldstein 2006)

A case of system transition. In this section we focus on the long transition period that started in the late 1980s and we claim is still ongoing. The opening up of the military-industry complex (MIC) and the expansion of civilian production has required fundamental institutional and organizational changes in an industry that at some point during this process employed over half a million people.

4.5. Empirical evidence of interruption and transition

Value added. We estimate that aerospace value added exceeded 4.8 billion dollars in 1983. Following a sudden drop in fighter aircraft production, it fell to 2.1 billion by 1987 and continued to decrease to the 1996 low of 1.4 billion USD. After a turnaround, with an average growth of over 16%, by 2005 the value added of Chinese aerospace industry exceeded the levels of the early 1980s. In 2007 it reached a historic 7.1 billion USD (Figure 14). However, it is important

Exports. The composition of the industry’s exports shows a striking change. Between 1970 and 90, China exported an annual average of 0.5 billion dollars of (mostly locally manufactured) military planes. During the following two decades this amount was halved. At the same time commercial aircraft parts and components exports grew from some 100 million dollars at the beginning of the 1990s to over 1 billion USD by 2007 (Figure 15). Nevertheless, China continues to import almost all of its commercial aircraft\(^\text{31}\).

\(^{31}\) Import (of mostly complete aircraft) grew from 1.6 billion in 1992 to over 8.4 billion USD in 2006.
**Figure 15** Export of Chinese Military and Commercial Aircraft, 1955-2008 (USD Millions, Constant = 2000)

![Chart showing export of Chinese Military and Commercial Aircraft, 1955-2008](chart.png)

*Source: SIPRI; UN COMTRADE (data only available from 1992)*

**R&D.** Data on aerospace R&D is available from 1995. From an annual average of 100 million USD until 1999\(^{32}\) the launch of major national aircraft development projects led by 2007 to an increased R&D expenditure of 430 million USD\(^ {33}\). Comparing industrial R&D expenditure to aggregate sales shows relatively little fluctuation and an increasing share of R&D (Figure 16).

**Figure 16** R&D Expenditure and R&D per Sales in Chinese Aerospace Industry, 1995-2007 (USD Millions, Constant = 2000)

![Chart showing R&D expenditure and R&D per sales](chart2.png)

*Source: China National Bureau of Statistics.*

*Note: Annual Average exchange rate in 2000 of 8.28 CNY/USD was applied (IMF).*

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\(^{32}\) For a comparison, during the same period Embraer alone spent the same amount on R&D.

\(^{33}\) In comparison, in 2000 the US spent a total of 10.3 billion USD on aerospace R&D, and 14 billion in 2006.
4.6. Legacies of the Military-Industry Complex (MIC)

Although China at its peak in 1974 produced over 500 aircraft, these were always at least a generation behind the global technology frontier due to difficulties in acquiring required technologies (Frankenstein and Gill, 1996). Chinese design and production plants had to substitute the previously available Soviet technology with reverse-engineering after the 1961 Sino-Soviet split. The MIC, constructed but also obstructed by national security concerns, has never emerged to be a fully functional sectoral innovation system. Unlike in Brazil where aerospace industry concentrated around the single Sao Jose dos Campos cluster, at least a dozen of centers were created around China designated with aeronautical R&D, maintenance and production work. The most important production facilities (or machine building industries with a code number) were located in Shenyang and Harbin in the northeast, Chengdu in the southwest, as well as around Shanghai, Xian and Taiyuan. Aircraft factories oversaw hundreds of enterprises and also produced non-aviation products to utilize idle capacities. Productivity was not a major concern for the division of labor between these factories and multiplication of tasks was common due to lack of linkages between parallel projects. The organization of the industry showed a ‘satellite pattern’.

Supervision and coordination of R&D and production activities was the responsibility of the Commission on Science, Technology and Industry for National Defence (COSTIND), a body reporting both to the People’s Liberation Army (PLA) as well as to the State Council. The only source of finance was the government (the military or state council), and the expenditures on various projects remained concealed. Production cycle of military aircraft is a bright illustration of political events (Figures 15)

While research and engineer training was located around the production facilities, university level education in disciplines related to aerospace were offered in Beijing (BUAA) and Nanjing (NUAA).

Figure 17 Estimated Chinese Jet Fighter Production, 1960–1995

![Bar chart showing estimated Chinese jet fighter production from 1960 to 1995.]

Source: Allen et al (1995, Fig.17, p.162)
Note: This figure clearly indicates the influence of major political events: the Sino-Soviet split of 1961, the Cultural Revolution during the late 1960s and the reforms of Deng Xiaoping following 1978.
4.7. The origins of commercial production

Even before the more fundamental institutional changes of the 1990s, there were several attempts to diversify into the production of commercial aircraft. The Y-10 project of the 1970s proved that Chinese engineers were capable of designing prototypes of a large civil aircraft that flew. However, the project never reached the phase of serial production and was cancelled in 1983, as it did not turn out to be commercially viable and the Aviation Administration of China preferred to import more modern planes. The MD-80 assembly project was the first bold sign of opening up the industry to western technology and commercial production. In 1985 China signed a license agreement with McDonnell Douglas (MD) to assemble the MD-80-series medium range jets in Shanghai. The airplanes were assembled from kits with some components fabricated in China. MD provided technical data, training, and on-site assistance. 35 planes were produced between 1985 and 1994, mostly for the local market (30 were sold to China Northern and China Eastern and 5 were exported to the US). The Shanghai-produced planes were however repeatedly experiencing technical failures and collect only a modest amount of flying hours. A renewed contract for 20 Chinese MD-90s Trunkliner with an indigenously produced share of 80% resulted in only 2 planes delivered for China Northern in 2000. Despite the low productivity and quality problems, the technology acquired through this endeavor gave a major push for the industry, and founds its way to the first indigenous design, the ARJ-21 regional jet as well.

Quality problems hampered the success of a smaller-scale project, the multiuse turboprop military / civilian transport plane based on Soviet Antonov design, the Xian Y-7 or later MA-60. Already these projects included collaboration with Western partners. These Chinese made planes had limited success on the export markets since western administrations did not certify the planes due to quality concerns and most of them were eventually grounded for safety reasons or lack of spare parts.

4.8. A slow transition

The transition in the aerospace industry and innovation system was part of major market reforms in China. The iterative but fundamental institutional changes in the national innovation system were correctly described as ‘adaptive learning’ (Gu and Lundvall, 2006). Certain heavy industries (including automobile) were consolidated in a shorter time, but aerospace remains a slow mover, given its sheer size (employed nearly 0.6 million in 1995), the reluctance of chief financing and regulating bodies of the military to change their mindset. Following a 1991 order of the more demand-conscious government, the PLA was to shift 80% of defense manufacturing to commercial products (Allen et al, 1995), in order to tackle financial difficulties. The successful transition of other industries certainly serves as an example for aerospace.

34 Although the Y-10 shows a high degree of similarity to the Boeing B-707, Chen (2009) argues that some of its features outperformed the B-707, thus it was innovation, not merely imitation.
35 It was based on 1950s technology and Boeing stopped producing the 707 in 1979 due to its high fuel consumption. Political reasons might also have played a part: possible pressure from the US as well as the end of influence of the ‘Gang of Four’ who were behind the project.
36 During the twenty years period of its production, the US produced over 1000 of these planes making it the third most successful jets in history, China only assembled 35, most of which were very soon grounded.
Demand for air travel spurred by growth of the economy has been a major driving factor of industrial change. Both international and domestic air traffic have increased dramatically since the late 1980s. However, the air transport market remains tightly regulated and aircraft load factors and flying hours remain suboptimal, airport capacities underused (Goldstein, 2006).

### 4.8.1 Foreign aircraft manufacturers in China

While importing most of the aircraft from Boeing and Airbus, China pushed for offset agreements to simultaneously support the technological upgrading of the industry. At first this meant less technology-, more labor-intensive parts (hardware) manufacturing at dozens of locations across the country. Production quality increased substantially as a result of these deals since Chinese suppliers had to deliver according to the same strict standards as others faced in the West. The initial political necessity to produce in China soon became an economic advantage for Western manufacturers as they reaped the benefits of lower labor costs (notwithstanding the initial learning costs). However, Chinese contribution remained at the lower tiers of the earlier discussed, newly established global industrial structure. Only in 2009 was first risk sharing partnership venture signed by a Harbin-based consortium and Airbus for the A-350 XWB project. The first foreign manufacturer to commence final assembly of jets in China was Embraer. The Harbin Embraer joint venture of 2003 allowed the Brazilian company to deliver ERJ-145 regional jets for the Chinese market by avoiding import taxes while acquiring certain parts manufacturing and systems assembly was a major technological boost for the Harbin plant. The results of the venture were mixed: by the end of 2009 only 33 of the original order of 50 jets were delivered although the company had a capacity to produce 24 a year and was expecting new orders. The last of the ERJ-145 is expected to be produced in 2011 and Embraer is now awaiting government decision to approve a shift to ERJ-190 production, otherwise it plans to close down the plant. The Chinese government is hesitant since it would be a direct competitor of the locally developed ARJ-21 (Asian Regional Jet for the 21st Century), due to enter series production in the same time horizon.

Airbus also established a joint venture for final assembly in China. Operations commenced in 2008 at the Tianjin final assembly line (FAL), a replica of Airbus’ Hamburg plant. The first A320 was delivered mid 2009. At moment, production capacity is 4 aircraft a month. Airbus initially assembled aircraft from kits delivered from Europe, gradually changing to locally made parts. The total investment in the

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37 Passenger air traffic doubled between 1985 and 1990 to 23 billion passenger kilometer. This value nearly tripled by 1995 to 68 billion, still merely 10% of US air traffic. It further tripled to 200 billion by 2005 and latest figures show 290 billion by 2008 (CNSB).
39 The joint venture is special since it allowed a 51% majority ownership for a foreign company. For more details on the 50 million USD deal, see Goldstein (2006).
42 Airbus owns 51% share while the rest is divided by a consortium of AVIC and Tianjin Free Trade Zone.
43 Avoiding double shipment by directly using components i.e. wing boxes produced by Xian Aircraft Industry Group.
Tianjin FAL amounted to 1.47 billion USD\textsuperscript{44}. While Boeing was not ready to take the risk of going to China, Airbus expects long term benefits of market access exceed the initial investments.\textsuperscript{45}

\textbf{4.8.2. ‘Indigenous’ aircraft development}

Chinese ambitions to boost the industry have been high. The 11\textsuperscript{th} Five-Year Plan for 2006-2010 included the completion of the ARJ-21 regional jet project and the launch of a large aircraft development project for civil and military use, supposed to fly by 2015.\textsuperscript{46} Although indigenous in name, both projects utilize global technological and investment capacities, following the risk sharing partnership practice of Western aircraft producers. The ARJ-21 project that started in 2002 still reflects many of its local technological origins. Coordinated by a government-led commercial aircraft company (ACAC, later COMAC)\textsuperscript{47}, the four plants involved (Shanghai, Xian, Chengdu and Shenyang) were the same as the ones in the MD-90 \textit{Trunkliner} project and it is hard not to notice the resemblance of certain sections\textsuperscript{48}. The largest share of development costs of the first regional jet project, the ARJ-21 were provided by COSTIND, but leading transnational companies participate in financing the development.\textsuperscript{49} The US Federal Aviation Authority (FAA) has been involved in the development process in order to facilitate certification. The fact that the “First Chinese Made Plane” will not bear “Made in China” tags indicates of the maturity of Chinese design and organizational capabilities. The arrangement of acquiring technology and finance through risk sharing partnerships is similar to the strategy Embraer chose in the mid 1990s, but for the arrangement to work efficiently, private ownership of Embraer was crucial.

The ARJ-21 made its maiden flight at the end of 2008 and four prototypes are currently undergoing tests. Serial production and the establishment of a distribution network has not even begun when the government announced the plans to develop a large civil aircraft\textsuperscript{50} in the 168-190 seats category. The COMAC C-919\textsuperscript{51} would be a direct

\textsuperscript{44}“Airbus delivers first China-made jet, underlining its Asian thrust”, Agence France Presse, 23 June 2009.
\textsuperscript{45} Production is cheaper in China mainly because of (some) reduction in import taxes and duties. The lower labour costs in China are however not necessarily realized in the short run given the high training costs for local labor force and the cost of expatriates (125 of the 500 employees). (“Airbus’ China Gamble” Flight International 28 October 2008)
\textsuperscript{46}“Official identifies eight goals for China’s aviation, aerospace industry”, BBC Monitoring Asia Pacific, 9 Nov 2006
\textsuperscript{47} ACAC, or ‘AVIC-I Commercial Aircraft Company’ was a consortium of four main companies under the AVIC I conglomerate, designated to oversee the development, certification and marketing of commercial aircraft. In 2009 the company became part of COMAC, the ‘Commercial Aircraft Corporation of China Ltd’ established in 2008.
\textsuperscript{48} Highly similar parts include the nose, produced by Chengdu, the fuselage by Xian, the tail section by Shenyang or the horizontal stabilizers by Shanghai (Andersen 2008). The aircraft was thus aptly named \textit{Xiangfeng} (flying phoenix), as it was revived from the ashes of the failed MD-90 \textit{Trunkliner}.
\textsuperscript{49} Foreign partners include Antonov (wing design and testing), General Electric (regional jet engine development), Rockwell Collins (avionics), Hamilton Sundstrand (electric system and auxiliary power unit and fire protection system), Eaton (control panel), Liebherr (landing gear). Boeing has been providing engineering consultancy and cockpit design assistance.
\textsuperscript{50} ‘Large civil aircraft’ is a more appropriate term for this narrow-body jet than the often used ‘jumbo’, which normally refers to Boeing B-747s with a seating capacity in the range of 500.
\textsuperscript{51} The list of collaborating partners has not been finalized yet; currently Hongdu (Nanchang), Xian, Shenyang and Chengdu Corporations are the Chinese companies involved (“China’s Comac brings more suppliers in, Flight International, 24 Sept 2009”), while foreign companies already chosen include many of the ARJ-21 partners: General Electric, Hamilton Sundstrand, Honeywell, Liebherr Aerospace and Parker Hannifin (based on respective company press releases).
competitor of the smaller Boeing and Airbus jets (B-737 and A-320 family), bringing new turbulence to a consolidated duopolistic market. Designing is China has yet to gain experience in setting foot on the international aircraft market, which involves winning the trust of passengers and airlines, establishing the maintenance, repair and overhaul network, and efficient supply chain management. This step is crucial to recover the huge sunk costs of development, and still requires vast investments domestically and overseas.

The Chengdu and Shenyang plants at the same time continued to produce enhanced versions of existing fighter jets and introduced new models, such as the Chengdu J-10\textsuperscript{52} or the FC-1 Brave Dragon. This latter aircraft is a joint development project with Pakistan and is intended for low-cost military markets (Medeiros, 2005)\textsuperscript{53}. A fighter-bomber (JH-7) was developed in Xian during the 1980s and 1990s. Both the existing stock of aircraft and the latest developments represent at least one generation behind the technological capabilities of the US while onboard systems and mass-production capabilities are still further behind. But the real competitor of China is not in America but in Asia: “Right now, the only arms race China is really facing is with India, and [Beijing is] winning,” quotes the influential industry journal Aviation Week and Space Technology\textsuperscript{54} with regard to the development of a fifth generation stealth fighter.

4.8.4. Organizational changes

These developments in the accumulation of technological capabilities were set against a dynamically changing organizational structure. The first sign of opening up the MIC was the creation of Aviation Industries of China (AVIC) conglomerate in 1993 (controlling all the aeronautic research and production facilities) and China Aerospace Corporation (CASC, in charge of the aeronautic programs and missile system development and production). Driven by the need to plant the seeds of competition, AVIC was split into two in 1999\textsuperscript{55}. Duplications and a lack of transparency and unclear areas of responsibilities still remained in the system which eventually led to a 2008 decision to once again merge the two. One clear result of these bureaucratic twists is a drastic decrease of employment. As Figure 18 shows, employment in the industry shrunk in a decade from some 600,000 in 1995 by half to a stable 300,000. Labor productivity increased from 1995 to 2000 by 87%, between 2000 and 2007 by 366%. These are evident signs of consolidation in the industry, even if this might not remain the final setup. Nevertheless the structure remains “extremely complex” with cross-

\textsuperscript{52}The J-10 is an F-16-class fourth generation light fighter jet with fly-by-wire control and a Russian engine, launched in 1988, first flew in 1996. It is believed to have received direct technological input from the Israeli Aircraft Industries’ discontinued Lavi program (which received input from the F-16 program), though it was denied by both parties as it would imply American technology transferred to China. (Medeiros, 2005 and “Chinese J-10 ‘benefited from the Lavi project’, Jane’s Defense News, 19 May 2008; http://www.janes.com/news/defence/jdw/jdw080519_2_n.shtml )

\textsuperscript{53}The aircraft’s Pakistani designation is JF-17 Thunder, and development partners included Chengdu Aircraft Industries Corp., the Pakistani Air Force and Pakistan Aeronautical Complex; is equipped with a turbofan engine from the Russian Klimov. Design began in 1994 but the aircraft first flew only in 2003, produced in limited numbers since 2007/8 in China and Pakistan, while modifications are still underway.

\textsuperscript{54}“China Promises New, Advanced Fighter”, Aviation Week and Space Technology, 24 Nov 2009.

\textsuperscript{55}In general, AVIC I was responsible for producing larger planes, AVIC II for smaller, including helicopters. For details on the distribution of companies within, see Table 3 and 4 in Andersen (2008).

CASC was also divided in 1999 into China Aerospace Science and Technology Corporation (also CASC, in charge of the space programs) and China Aerospace Machinery and Electronics Corporation (CAMEC), later in 2001 renamed China Aerospace Science and Industry Corporation (CASIC).
ownership and a long line of cascading subordinates (Nolan and Zhang, 2002). Non-aviation business still makes up 80% of AVIC’s business (Medeiros, 2005).

Figure 18 Employment and Labour Productivity Growth in the Chinese Aerospace Industry, 1995-2007 (values in thousands of constant 2000 US dollars)

Source: CNBS.
Note: for Value added figures see notes of Fig.14.

4.9. Institutional challenges

The aggregate, industry level figures hide much of the details and internal structural changes and remaining hurdles that make the transition process last so long. Detailed information is still unavailable, but we can to point out the main institutional challenges and blockages that impede more increased performance of the sectoral innovation system(s).

1. **Ownership**: Decision making in the state-owned conglomerates remains slow and heavily laden with politics; foreign ownership in the sector is generally limited to less than 50% (exceptions are the case assembly facilities of Embraer and Airbus).

2. **Competition**: There is little competition among the producers, military procurement policies create sufficient domestic demand for local products; the latest Chinese products have yet to make gains on the export markets. Competition does not appear to pose an incentive for the rather well cushioned R&D institutes and are only less relevant feedback loops for innovative activities. It is unclear how much freedom various plants and R&D institutes have in defining the direction of research for new technologies and to what degree is there a domestic competition for government funds. The protective measures continue to keep the industry’s marketing capabilities at a less advanced level, but this is compensated by the size of the domestic market.

3. **Intellectual property rights**: The catch-up strategy appears to follow ‘the aims justify the means’ rationale. As long as lack of transparency and national

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56 Nolan and Zhang reports that automobiles, components and motorcycles alone accounted for 62% of AVIC’s revenue in 1997.

57 Military production appears to be divided by “market segment” served: light fighter jets are produced in Chengdu, heavy fighters in Shenyang, bombers in Xian; commercial projects are shared among the biggest factories.
security arguments prevail, IPRs are likely to continue to be an issue. Nevertheless major foreign private investors can enforce certain regulations (e.g. on employee retention) or hedge themselves by the high investment and learning barriers.

4. Access to technology: the arms embargo by the USA and the EU remains to be a major restriction on the flow of technology. Technology flows between military and civilian projects is expected to be limited, although interaction among the geographically dispersed units appears to be increasing in both domains.

5. Flow of skilled labor: compensation in the industry is not competitive with wages in coastal cities and enterprises with foreign investment; salaries are often still not determined by performance (Medeiros 2005); considering international flows, brain drain is more common than brain gain.

The transition of the innovation system will remain incomplete as long as many of these barriers are in place. The speed of institutional change is defined by the government (and the PLAAF) which is pursuing a strategy of slow transition. As long as the industry continues to grow (at a faster rate than other industries) and the government will have no problem in raising vast sums for new R&D missions, there will be no incentives to make changes in the innovation and production system.

58 The EU appears to be more flexible in its interpretation of the embargo and is more ready to consider a reform. See more details at Sipri “EU arms embargo on China”, (URL: www.sipri.org/research/armaments/transfers/controlling/arms_embargoes/eu_arms_embargoes/china)
5. Conclusion and Discussion

In sum, we have found evidence that sectoral systems of innovations changed over time. Innovation and production systems emerged through the accumulation of investment and technological capabilities and gained competitiveness in market segments. The latecomer countries with the best performing aerospace industries have been the ones that have managed to be competitive at least in one segment of the global market, as a result of systemic efforts from which the governments’ role remained crucial. Systems evolved incrementally due to endogenous forces. However, there were historical periods of major institutional rearrangements, triggered by crises. A drop in demand or a mismatch between innovation capabilities and demand resulted in interruptions that endangered the industry’s future. Yet, in some cases (e.g. Brazil, 1994 or China, late 1990s) the institutional setup was modified and allowed new records in innovative and productive performance.

The proposed interrupted innovation framework appears to be a useful tool to analyze historical development trajectories of the sector. Beyond its capacity to structure the qualitative analysis of institutional changes with regard to local context, it also exposes a number of more general, critical questions.

First, measuring transitions is not straightforward since innovation system performance is too complex to be captured in a single indicator. Looking simultaneously at the changes in input measures (R&D, skilled labor, technology), outputs (such as new products) and the industry’s value added has in the examined cases highlighted interruptions and transitions. To find out what institutions are relevant depends on the demand conditions and requires an in-depth study.

Second, what caused the transitions in the three cases? Endogenous factors resulted in incremental adjustment of the system, external factors (macroeconomic, political crises, or a changing demand for innovative solutions) were behind the transitions (Brazil, 1960s, 1990s; China: 1990s).

The non-linear nature of technological change, the lock-ins, the institutional rigidity (vested interests of powerful actors), uncertainties are important factors behind the cyclic pattern. It is also a question whether stability at the same time may be more conducive to capabilities accumulation.

Third, how can we predict new transition periods? Archibugi et al (1999) criticize the Galli and Teubal model (1997) for its lack of predictive capacity and the lack of evolutionary elements in it. Looking at when an industry emerges clearly depends on political factors. System transition appears to be predictable only if global business cycles can be predicted. Firms however play an important role in monitoring the signals of the competitive landscape in order to be ‘lobbyists’ for system-wide change. The lack of competitiveness-driven firms in the Chinese system may well be the reason for the nearly 20 year long transition during the 1980-90s.

This also raises a fourth question: who governs transitions? Since it affects a number of actors in the country, governments may have the most legitimacy to change institutions. On the other hand, firms (or entrepreneurs) face the competitive signals. Who pays the costs of transition, or who pays the costs of ‘non-transition’ may be an important issue in this regard. Higher social costs imply a greater role for the government.

Fifth, the question of substitutability is important in light of the apparent prevalence of path dependence. The availability of alternatives at historical periods of transition affects the outcome of institutional arrangement as well as the formation of new actors and ultimately, the performance of the innovation and production system. The question is whether it would have been possible to acquire similar technological capabilities had
the respective firms formed collaboration agreements with different actors. For instance, in the case of Brazil there were more options to choose from when deciding on technological partners, in China, substitutability was rather low at the formative phase but broadened with the opening up of the economy after 1978.

Finally, it is a question whether the framework is applicable to other industries as well. Sectors that combine high technological and capital entry barriers, a distorted market and high regulatory role of states poses a high limitation, but other transport equipment industries as well as some specialized segments of electronics (e.g. medical instruments) or energy sectors may be interesting cases to examine in a latecomer context. However, the availability of data remains a significant constraint for any similar analyses.

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