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Abstract:
Most of the studies that describe the building of innovation capability in emerging and developing economies have focused on the ways in which latecomer firms develop continuously towards advanced capability levels along existing technological trajectories, particularly for the assembled products industries, especially in Asia. A slightly different approach is adopted herein by focusing on pathways of discontinuous capability building of firms in natural resource-processing industries. By drawing on evidence from a variety of case studies taken from 13 forestry, pulp, and paper firms in Brazil in the period 1950-2007, it was found that: (1) in contrast with the majority of case studies reported in the literature, the pathways followed by firms in their accumulation of innovation capability involved a qualitative departure from the established technological trajectory at an early stage in the development of their capability; (2) the pathways of firms along the new technological trajectories were nevertheless characterised by a high degree of variability (from world leader to laggard) in terms of the levels and speeds of the accumulation of innovation capability; (3) firms that have attained progressively higher levels of innovative performance have more rapidly developed a combination of internal and external research-based arrangements in order to undertake increasingly complex, but firm-centred innovation efforts. This paper sheds some light on some of the discussions that relate to the role of natural resources in the patterns of industrial progress and growth in those countries endowed with particular natural resource-based industries. It also provides a methodological contribution to the study of the long-term innovation strategies that make use of the dynamics of capability building, especially within natural resource-processing industries.

Keywords: Technological trajectory; innovation capability; disruptive innovation; latecomer firms; natural resources; multiple case-study; Brazil

Jel codes: O34

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1 Introduction

Since the late 1980s, researchers have sought to examine the means by which firms and industries in newly industrialised Asian countries have narrowed their capability gap with that of world leading firms (see Amsden (1989), Hobday (1995), Kim (1997), Mathews (1997), and Mathews and Cho (1999)). Most of their studies have drawn on existing approaches to technological catch-up (Kim, 1980; Dahlman et al., 1987; Perez and Soete, 1988). A significant body of subsequent empirical work emerged in the late 1990s that scrutinised the nature of the paths by which innovation capability was accumulated in some of the assembled products industries in Asian countries, such as those of electronics, automotive, and capital goods (Choung et al., 2000; Lim and Lee, 2001; Mathews, 2002; Amsden and Chu, 2003; Hobday et al., 2004; Mu and Lee, 2005; Lee et al., 2005; Choung et al., 2006). Feng and Ling (2007) described the process by which Chinese firms achieved high levels of capability in architectural innovation in DVD players without even having the capability to produce them, while Zeng and Williamson (2007) examined "cost innovation" pathways that involved the exercise of their abilities in process and product innovation to create new kinds of electronics products and unique market positions. The change from technology following to technology creation for a new generation of mobile systems in China was examined by Yu (2007).

The kinds of studies mentioned above are consistent with the frameworks that have been described to interpret the economic catch-up processes that have taken place in various assembled products industries in Asian countries, such as the development of manufacturers from third-party design (OEM) to being own-design (ODM) and own-brand (OBM) (Hobday, 1995), and Linsu Kim's *Imitation to Innovation* framework (Kim, 1997). By building on these frameworks and on other Korean studies, Lim and Lee (2001) developed a classification that identified three modes of catch-up, namely *path-following* when latecomer firms follow the same path as that taken by their forerunners (although for a shorter period of time), *stage-skipping* when latecomer firms follow the path to an extent but skip some stage (thus saving time) and *path-creating*, when:

> "... latecomer firms explore their own path of technological development. This kind of catching-up can happen when the latecomers turn to a new path *after* having followed the path of the forerunners, and thereby, create a new path" (p. 465, my italics).

The foregoing body of empirical research, and classifications like Lim and Lee's (2001), have provided illuminating evidence and analyses of latecomer firms' technological catch-up. Lim and Lee's (2001) study, in particular, offered a broader set of perspectives on catch-up, which has stimulated further investigation of different kinds of catch-up experiences. Nevertheless, some issues and contexts have received scant attention in these and other related studies in recent years.

Firstly, in most of the studies the process of building innovation capability has been studied by assuming the existence of a *long-term continuity*. Most studies address the accumulation of a firm's capability by considering (successful) technology-following trajectories. In most cases firms switch into path-creating trajectories *later on*. However, the phenomenon of discontinuity, either in terms of early departure from an existing trajectory or in relation to the truncation of the process of capability accumulation, has received less attention. There have been a few initiatives in this direction. Dutrénit (2000), for example, explored elements of *truncation* in capability building that were associated with a firm's somewhat limited innovation strategy. Viotti (2002) deems such *truncation* as an "inherent" weakness of Latin American firms in moving from incremental to sophisticated levels of innovation. Other studies have sought to tackle the problems involved in latecomers' *transition* to being leaders in innovation, e.g. Amsden and Tschang (2003) and Hobday et al. (2004). Neither of these two latter studies scrutinised *qualitative discontinuities* in firms' capability building.[1] And neither examined how firms negotiated such discontinuities or how they differed in so doing.

Secondly, some studies that took place in the 1980s showed awareness of the importance of the timing involved in the accumulation of capability. Dahlman et al. (1987), for example, pointed out that it takes considerable time to move through the different stages of innovation capability, while Perez and Soete (1988) indicated that catch-up also involves developing the firm in new directions. In a similar vein, Lee (2005) argued that "the speed of progress on the track has been uneven, with some catching up rapidly and others lagging behind" (p. 98). However, as noted in Bell (2006), most of the empirical studies of latecomer firms' capability building, especially those from the 1980s, have given only limited attention to the issues of the timing and speed at which firms move (or fail to move) from basic to advanced and/or 'frontier' innovation levels.

[1] In the context of this paper "qualitative discontinuity" means a shift in the innovative capability accumulation process that may enable the firm to pursue a different direction of technological development from that already followed by the global leaders. This is done by opening up a qualitatively different segment in the international technological frontier.

Thirdly, the great majority of studies of capability building, especially those within an Asian context, have examined firms and industries founded on assembled and discrete products. Capability building here normally involves a progression from assembly to low-part development, high-tech development and finally to conceptual design capability for products (see Lim and Lee (2001)). This is understandable because these sectors have been the main drivers of industrial growth in East Asian countries. During the past few decades, most of the academic studies and policy analyses of industrial development in emerging economies have focused on the role of “high-technology” industries and the “high-tech content” of exports in achieving economic progress (e.g. Lall (2000), and Lall et al. (2004)). Because East Asian economies were generally endowed with an abundance of labour and suffered from a paucity of natural resources, specialisation in manufacturing was a natural choice, although this factor alone was obviously not sufficient to achieve industrial leadership (Rodrik, 2006). The direction and dynamics of capability building in firms in regions rich in natural resources like Latin America is not well understood, however, and suffers from a dearth of systematic firm-level scrutiny.

In relation to industrial development in countries rich in natural resources, consideration must be given to the so-called “natural resources curse”, in its claim that those countries that depend on natural resources tend to experience periodic slow growth or stagnation in their economies (see Sachs and Warner (1999, 2001), and Mehlum et al. (2006)). An alternative line of argument holds that those problems that are normally associated with the abundance of natural resources are affected by the existence and functioning of *institutions* in specific countries (Stijns, 2001; Pessoa, 2008). The view supported by Wright (1990), which is more in line with the perspective adopted herein, holds that if natural resource industries are developed using sophisticated knowledge and expertise, they may have a positive effect on industrial and other sectors, including manufacturing. It is a matter of record that the agricultural, minerals, forestry, pulp and paper industries were important to progress in North America and Scandinavia (the Norscan countries), which were the leading innovators in the forestry, pulp and paper industries early on (see WESS (2006)). In line with Wright’s (1990) proposition, Perez (2008) and ECLAC (2008) hold that an intelligent combination of natural resource management and the building of innovation capability is viewed as a new “window of opportunity” for Latin America to improve its competitive position in relation to that of East Asia. However, there is a dearth of empirical analysis of the nature, extent and speed of the building of firm-level innovation capability in these industries in Latin America.[2]

Previous research has indicated that Brazil's forestry, pulp and paper industries offer a rich empirical setting for examining different pathways of firms' innovation capability bulding. For example, Scott-Kemmis' (1988) pioneering study examined the development of firm-level capability in these industries in Brazil (1940-1970) and captured some embryonic research and development (R&D) activities that formed the initial basis for the shift into the eucalyptus-based trajectory for pulp production. Later, Dalcomuni (1997) found that five large Brazilian pulp exporters achieved an internationally recognised environmental performance that involved some research of bleaching technologies for the pulp production process and some research linked to upstream forestry activities. There is a wealth of industry-level evidence indicating that Brazil has sustained a leading competitive performance in the world market for pulp and paper derived from eucalyptus forestry or "bleached eucapulp", with 58 percent of the world market share (see e.g. Evans and Turnbull (2004), FAO/PPI (2007), and BRACELPA (2008)). However, few studies exist that describe the extent of, and the speed at which, the innovative capabilities that underpin the competitive performance of firms in the forestry, pulp and paper industries in Brazil have been accumulated.

In a different context, Bell and Van Dijk (2003) and Van Dijk and Bell (2007) found that some local firms in the Indonesian pulp and paper industries, were rapidly able to narrow the gap between their *production* capabilities and those of other firms that operate at the international production frontier. Most of these local firms did not develop significant levels of *innovation* capability, however. Hardly any studies have scrutinised the manner and speed of the accumulation of firm-level capability and the achievement of innovative performance other than by the normal established route, particularly in the context of natural resource-endowed Latin America.

This paper seeks to extend previous research in the accumulation of latecomer firms' innovation capabilities by exploring some of the areas outlined above that have previously received less attention. Specifically, the nature and speed of the accumulation of innovation capability at the level of individual firms other than by the

[2] There is a wide-ranging debate concerning the "natural resources curse" perspective, in which I do not intend to engage here. Nevertheless, this paper offers a contribution to the understanding of the accumulation of firm-level innovation capability, in particular by examining the process by which latecomer firms overtake incumbent innovators in natural resource-processing industries.

established technology-following type of trajectory is scrutinised herein. This issue is examined for 13 forestry, pulp and paper firms in Brazil for the period 1950 - 2007.[3]

Using evidence from a variety of case studies, the results presented herein indicate that firms from the forestry, pulp and paper industries in Brazil have been engaging in a slightly different kind of 'path-creating' in their trajectory of accumulation of innovation capability. They began to diverge from the existing technological trajectory at an *early stage* of the development of their innovation capabilities. Just after World War II, these firms began to make pulp and paper from eucalyptus trees, and to engage in activities that firms in the Norscan countries were not engaged in. This meant that, relatively early on, they could not simply copy the recognised global leaders, and were instead forced to develop technologies more suited to their own somewhat different operations. This involved the use of different raw materials, and in developing the effective means to do this, they routinely used innovations in their operations. They could not simply *imitate* because they were developing along a different trajectory.[4]

Specifically, the process involved a *qualitative departure* from the trajectory previously mapped out by earlier innovators, thus opening up a qualitatively different segment at the international technological frontier. The pathways of Brazilian firms along these so-called "variant" technological trajectories, were far from being a total success in that they were marked by a high degree of *variability* in the level of, and speed by which, innovation capability was built up. Such processes of accumulation of capability are slightly different from those described in Lim and Lee's (2001) *path-creating catch-up mode*. This paper explores the manner in which some firms in Brazil have carved out and sustained. The remainder of this paper is structured as follows. Section 2 outlines the paper's analytical background and framework, while Sections 3 and 4 contain the empirical setting and research methods, respectively. Section 5 presents the empirical analysis and discussions and the conclusions are given in Section 6.

[3] The issue of the role of industrial policy regimes in influencing the process of accumulation of firm-level innovation capability is beyond the scope of this paper. The relationship between these two issues is examined elsewhere (see Figueiredo (2009)).

[4] I thank Richard Nelson for commenting on this finding and advising me to discuss it at the beginning of the paper.

2 Pathways pursued by latecomer firms in accumulating innovation capability

This section provides the analytical grounding for examining the pathways followed by the latecomer firm in accumulating innovation capability in a discontinuous manner and its reflection on its innovative performance. The capabilities of firms include a stock of resources that permit them to undertake *production* and *differing degrees* of innovation activity. Such capabilities are both in the nature of 'human capital' (i.e. specialist professionals, knowledge bases and skills/talents that are formally and informally allocated within specific organisational units, projects and teams) and 'organisational' (the firm's internal and external organisational arrangements such as their routines and procedures, linkages, managerial systems, including the firm's values, norms and beliefs that are reflected in its management style and behaviour e.g. in the form of entrepreneurial management or ambitious innovation strategies, see Bell and Pavitt (1993), Leonard-Barton (1995), Kim (1997, 1998), Dutrénit (2000), and Teece (2007)).

Following the convention used by Bell and Pavitt (1993, 1995), this paper makes the distinction between *production-based* and *innovation* capabilities. The paper focuses on the accumulation of the latter capability, because the concern here is with the accumulation of "path-creating" innovation capability, referring to the resources required to create, change or improve products, processes and the organisation of production.

The manner of, and the speed at which, the building of a firms' capability proceeds over time determines the types and levels of innovative activity that firms can undertake, i.e. a firm's *innovative performance*. This paper adopts a view of innovation that involves increasing *degrees* of novelty and complexity in terms of the processes, products and organisation employed, and is thus in line with the Oslo Manual (see OECD, 2005). This approach is most appropriate for latecomer firms. In line with such a perspective, the process of innovation also includes the use of "new combinations" of knowledge – e.g. to develop new sources of raw materials (Schumpeter, 1934; Kleine and Rosenberg, 1986).

The notion of the accumulation of capability (technological catch-up) in this paper reflects a narrowing of the gap between firms in terms of their capability to undertake *innovative* activities, or in other words, it means closing the gap between a firm and the innovation "frontier". However, the term "catch-up" suggests a single pathway, with different firms distributed along it, with a clearly defined “frontier”[5]. Specifically, the notion of a frontier tends to be associated with that of all firms following the same specific technological path (towards the same end-point) as that previously followed by global technological leaders[6]. In reality, the process of technological development of latecomers cannot be represented using the analogy of a race along a fixed track, because of the possibility of successful overtaking by latecomers moving in new directions, and of the emergence of radical discontinuities that open up opportunities for them (see Perez and Soete (1988), and Lim and Lee (2001)). By such means, latecomer firms may accumulate capabilities by which they may pursue significantly new *directions* of innovation that depart from the trajectories previously mapped out by earlier innovators, thus opening up *qualitatively different segments* of the international innovation frontier[7]. In this paper the notion of catch-up therefore also encompasses so-called “overtaking”. In addition, rather than deeming the technological frontier to be an end-point or even a moving target, it is considered here to be a fluid area or horizon to be explored.

Such fluidity of the technological frontier may be explored by new entrants, like latecomer firms, by developing discontinuous or disruptive innovations which will challenge the position of incumbents firms (Christensen, 1997; Christensen and Raynor, 2003; Bessant, 2005). Such discontinuity may be triggered by a number of factors among them step changes in process and product technology, recombination of different streams of knowledge (Bessant, 2005), but also in terms of new raw materials as in the case of the firms studied here. Following Christensen (1997) this paper distinguishes between low-end and new-market disruptive innovations. While the former takes place on the basis of cheaper products and processes and evolves to address the incumbents’ customers, the latter targets a different type of consumer. Firms may start in a typical low-end market segment and, on the basis of their innovation capability accumulation, evolve into value-added products in high-end segments as it seems to be case of some of the firms examined here.

The traditional indicators of innovation that are based solely on R&D expenditure, and on personnel and patenting statistics, are not well suited to capturing data on the pathways of innovative capability for latecomer firms (see Bell (2006), Bell and Pavitt (1993), and Lall (1992)), especially those in the pulp and paper industries (see

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[5] Richard Nelson, 2008, personal communication.
[6] Martin Bell, 2008, personal communication.
[7] Martin Bell, 2008, personal communication.

Laestadius (1998)). As a consequence, this paper draws on a modified version of the Lall/Bell and Pavitt typology (see Bell and Pavitt (1995), and Lall (1992)), which identifies "levels" of innovative capability that range from "basic" to "world leading" and are consistent with the Oslo Manual (a condensed version of the framework is given in the Table in Appendix). Such classifications have been used successfully in empirical studies, with slight variations in terminology (see Hobday et al. (2004), Figueiredo (2003), Ariffin and Figueiredo (2004), Tsekouras (2006), Dantas and Bell (2006), and Iammarino et al. (2008)). Rather than identifying capabilities in terms of the specific resources entailed therein, these works have identified levels of innovative *activity*, and then inferred the different levels of capability that lie behind the patterns of *innovative performance*.

Although the above framework emphasises those capabilities that are internal to the firm, it also recognises that a substantial part of a firm's capability to innovate is grounded in the activities of other organisations (e.g. consulting firms, research institutes, universities). Consequently, the building of innovation capability is not necessarily confined within the boundaries of a firm, but may instead involve several interdependent actors. However, in order for the firm to gain access to such a breadth of knowledge, it must nevertheless build up a substantial level of in-house expertise (Mowery, 1983) or absorptive capacity (Cohen and Levinthal, 1990), as well as a demand for local R&D outputs (Bell, 1993). Such an approach is particularly appropriate when latecomer firms engage in the accumulation of path-creating innovation capability at an *early* stage in their development, as examined herein.

3 The forestry, pulp and paper industries in Brazil: a brief overview

The forestry, pulp and pulp complex in Brazil consists of 220 firms located in 17 states. It accounts for 1.5 percent of Brazil's GDP (2006) and represents one of Brazil's leading export activities. Around 15 firms are responsible for nearly 90 percent of the total output and most of these are located in the South East of the country. Brazil is the leading producer of eucalyptus pulp or "bleached eucapulp" (short fibre) globally with 58 percent of the world market share (FAO/PPI, 2007; BRACELPA, 2008). In 2007, Brazil ranked 6th in the world in pulp production (eucalyptus and pine) and 11th in paper production. All of the pulp and paper produced in Brazil is derived from planted forests. Brazil is in a world leading position in the production of forestry for pulp and paper, as shown in Table 1. This factor enables a higher quality of pulp and paper to be produced at lower cost, and thus gives Brazil a more competitive edge than its rivals. Such a position has been achieved via the technological advances made by the leading firms, as discussed in Section 5.

Table 1. Some indicators in forestry for pulp and paper (2007)

	Brazil	Chile	Indonesia	Canada	Sweden	Finland
Proportion of planted forest in the country's territory (percent)	0.6	2.9	4.4	n.a.	n.a.	n.a.
Rotation of trees (hardwood: short fibre) – number of years	7 (eucalyptus)	10-12 (eucalyptus)	n.a.	n.a.	35-40 (birch)	
Productivity of short fibre species – hardwood (m^3/hectare/year)	41 (eucalyptus)	25 (eucalyptus)	20 (acacia)	n.a.	6 (birch)	4 (birch)
Rotation of trees (softwood – long fibre species)	15 (pine spp)	25 (pine radiate)	n.a.	45 [a] (oregon pine)	70-80 (picea abies)	
Productivity in long-fibre species – softwood (m^3/hectare/year)	35 (pine spp)	22 (pine radiate)	n.a.	7[b] (oregon pine)	4 (picea abies)	
Forest area needed to produce one million tonnes of pulp/year	100,000 ha	n.a	n.a.	n.a.	720,000 ha.	

Sources: Elaborated on the basis of data from BRACELPA (2008). *Note*: (a) and (b) = Coastal area.

The widespread distribution of planted forests is a renewable resource that is used in a variety of industries that base their activities on the use of raw materials from fibres and lignocelluloses, in particular the pulp and paper industries. The building of innovative capability in the upstream forestry segment (e.g. silviculture research in biotechnology for mass propagation and tree improvement) has an important role to play in improving the innovation and competitive performance of the downstream pulp and paper-making processes (De Assis, 2001). In order to understand how Brazil has been able to compete successfully against the global leaders from the Norscan countries, it is necessary to investigate the process that began in the 1950s, by which innovation capability has been built up in the upstream forestry segment (see Section 5).

4 Research design and methods

This paper presents results from an empirical study based on a three-year fieldwork campaign involving 13 firms from the forestry, pulp and paper industries in Brazil. In accordance with the demands of the analytical framework, the study underpinning this paper was designed using multiple case studies as it permits a more detailed investigation of the processes involved than other methods (Eisenhardt 1989; Yin 2003; Eisenhardt and Graebner, 2007). Specifically, the study is centred on particular segments (focal cases) within these firms, namely seven cases in forestry, nine in pulp, and 11 in paper (see Table 2). The study thus seeks to draw on an embedded design (Eisenhardt and Graebner, 2007) that encompasses studies both *across* the 13 firms and *within* them.

Table 2. The selected multiple cases

Thirteen selected firms	Start-up year	Ownership	Focal cases		
			Forestry [7]	Pulp [9]	Paper [11]
1. Delta	1945	Brazilian	✓	✓	✓
2. Theta	1974	Foreigner	✓	✓	✓
3. Kappa	1941	Brazilian	✓	✓	✓
4. Zeta-A	1954 (1990)	Brazilian	✓	✓	✓
5. Sigma-A	1988	Brazilian	✓	✓	✓
6. Alpha	1978	Brazilian	✓	✓	None
7. Beta	1975	Foreigner	✓	✓	None
8.Gama	1960 (1990)	Foreigner	None	✓	✓
9. Sigma-B (a)	1988	Brazilian	None	✓	✓
10. Epsilon	1980 (1990)	Brazilian	None	None	✓
11. Zeta-B	1985	Brazilian	None	None	✓
12. Iota	1978	Brazilian	None	None	✓
13. Lambda	1966	Brazilian	None	None	✓

Note: (a) Sigma-B does have forestry operations, but this business was not included in this study.

The cases were carefully selected using the following criteria: (i) the firms account for nearly 85 percent of the pulp and paper output in Brazil; (ii) they are large exporters and domestic market suppliers; (iii) some of them are top players in world market; (iv) most of them have played an important role in the formation and development of these sectors in Brazil; and (v) their activities reflect a variety of catch-up pathways (both successful and less successful), thus providing the basis for analytical generalisation. The implementation of this study sought to draw on protocols to establish solid *construct validity* and *reliability* (Eisenhardt, 1989;Yin, 2003; Shadish et al., 2002).

The exploratory phase of the fieldwork sought to test the research questions and analytical framework, and to negotiate access for data collection with the firms concerned. The tools for data gathering comprised a combination of (i) a matrix of types and levels of capability (see the Table in Appendix), (ii) a structured interview guide, and (iii) a detailed enquiry form. Data collection during the pilot phase and the main fieldwork involved a triangulation strategy consisting of 155 formal interviews (from one to three hours in length), 44 informal interviews, 19 direct observations and 27 consultations of firms' archival records.

Interviews were conducted with professionals from different levels in the organisation (e.g. top and intermediate management, supporting units like R&D, human resources, engineering departments, laboratories, the shop floor and forestry sites). The interviews were never recorded, but written records of the conversation were made. Techniques of snowballing and cross-checking with a third interviewee proved helpful in clarifying any discrepancies and in obtaining the precise details of specific projects. Double-checks of specific events were made using e-mail and/or by phone. Following the main fieldwork, 259 follow-up questionnaires were sent out to targeted respondents. Because they already knew the project and the researcher, a 95 percent response rate was achieved. Eleven formal interviews and 15 archival consultations were made at industry-related organisations (e.g. industry associations, consulting firms, suppliers, universities and research institutes).

Considering that the study examined firms' historical timeline of changes in capability accumulation, especial efforts were made to collect sufficient evidence to substantiate the reconstruction of their technological paths. This was undertaken by scrutinising the firms' technological milestones provided by different interviewees (including retired staff), internal presentations and records, annual reports and independent news reports. Even so, it is difficult to obtain a complete accuracy of past events. This is one of the limitations of this study. Nonetheless, it was possible gather evidence from different types of sources to substantiate the study.

Formal data analysis was undertaken using descriptive and analytical tables that permitted the examination of the main stages of the process of building innovation capability over time (Miles and Huberman, 1984). Evidence of innovative activity over time in each case study was matched against the capability framework (the Table in Appendix). Qualitative evidence of capability was transformed into quantitative evidence in order to examine the speed with which each firm accumulated its innovative capabilities over time (as discussed in Sections 5.1 and 5.2).

Rather than reducing all qualitative data to quantitative observations, both types of evidence were used to enrich the empirical analysis. The qualitative evidence described in Section 5.3, in the form of narratives, helps both to strengthen the arguments and to establish causal relationships (see Dougherty, 2000), as well as to interpret the quantitative evidence. Following the completion of the main fieldwork, a *case study* *database* was established that contained all the transcripts from the interviews and observations and all the documents obtained from the firms.

5 Empirical findings and discussions

This section presents the main empirical findings and discussions using the framework described in Section 2. Sections 5.1 and 5.2 provide some scrutiny of the evidence of the levels of capability and the speed at which these levels were attained in the case-study firms during the period 1950-2007. Section 5.3 draws on qualitative evidence in order to examine the evolution of the firms' path-creating capability building. Section 5.4 contains a summary of the key findings and discussions.

5.1 Levels of accumulation of innovation capability for the focal cases

Figure 1 contains the evidence of the levels of the firms' capabilities obtained during the fieldwork period. These capability levels were accumulated within the new (eucalyptus-based) technological segment that opened up inside the existing trajectory. However, the process of capability building was far from being wholly smooth in these firms, being marked by a high degree of variability from world leading and advanced in innovation to laggard. This finding has had various implications for the innovative performance of these firms over time.[8]

[8] This paper does not consider levels of capability accumulated by the case-study firms as a measure of success or failure. The purpose is to explore heterogeneity across the case-study firms in terms of the extent of and speed at which they have moved along the new technological trajectory.

Figure 1. Accumulation of innovation capability along the eucalyptus-based technological trajectory

	Capability levels	Forestry cases	Pulp cases	Paper cases
Innovation capability	World leading innovation ⇪	Alpha, Theta, Sigma-A, Delta, Kappa [**71%**]	Alpha, Delta, Sigma-A, Sigma-B, Kappa [**56%**]	Delta, Kappa, Sigma-A, Sigma-B [**36%**]
	Advanced Innovation ⇪	Alpha, Theta, Sigma-A, Delta, Kappa, Beta **[86%]**	Alpha, Delta, Sigma-A, Sigma-B, Kappa, Gamma, Beta [**78%**]	Delta, Kappa, Sigma-A, Sigma-B, Gamma, Zeta-B, Theta [**64%**]
	Intermediate innovation ⇪	All [**100%**]	All **[100%]**	All [**100%**]
	Basic innovation ⇪	All [**100%**]	All [**100%**]	All [**100%**]
Production-capability	Advanced production ⇪	All [**100%**]	All [**100%**]	All [**100%**]
	Basic operations ⇪	All [**100%**]	All [**100%**]	All [**100%**]

Source: Derived from the empirical study.

Source: Derived from the empirical study.

Evidence from Figure 1 suggests that six of the seven forestry-based firms (i.e. 86 %) reached an advanced level of innovation capability (Alpha, Theta, Sigma-A, Delta, Beta and Kappa), of which five firms (Alpha, Theta, Sigma-A, Delta and Kappa) attained the world leading level of innovation. Seven of the nine pulp-based firms (i.e. 78%) accumulated an advanced level of innovation capability (Alpha, Delta, Sigma-A, Sigma-B, Gamma, Kappa and Beta), of which five (Alpha, Delta, Sigma-A, Sigma-B and Kappa) attained a world leading level of innovation capability. Of the 11 paper-based firms, seven achieved the accumulation of advanced innovation capability (Delta, Kappa, Sigma-A, Sigma-B, Gamma, Zeta-B, and Theta). Of these, only four firms (Delta, Kappa, Sigma-A, Sigma-B) achieved world leading capability levels.

Some firms (Alpha, Kappa and later, Sigma-A and Sigma-B) have engaged in R&D activities since their inception. Alpha, for instance, began to engage in research-based activities in the upstream (forestry) segment about 10 years before the start-up of its pulp mill. This means that Alpha was undertaking R&D activities even *before having built up production-based capabilities*. This is similar to the findings of Feng and Ling (2007) in a different kind of industry, as noted in Section 1. In addition, while Sigma-A, Sigma-B, and Delta reached levels of world leading capability in forestry, pulp and paper, Theta's path was highly variable: at the frontier in forestry, near the frontier in paper and relatively laggard in pulp. As suggested by the results from the fieldwork, this finding is related more to Theta's *strategic option* to place an emphasis on innovation in the forestry business, rather than to a failure to build up higher innovative capability levels in paper and (more so) in pulp.

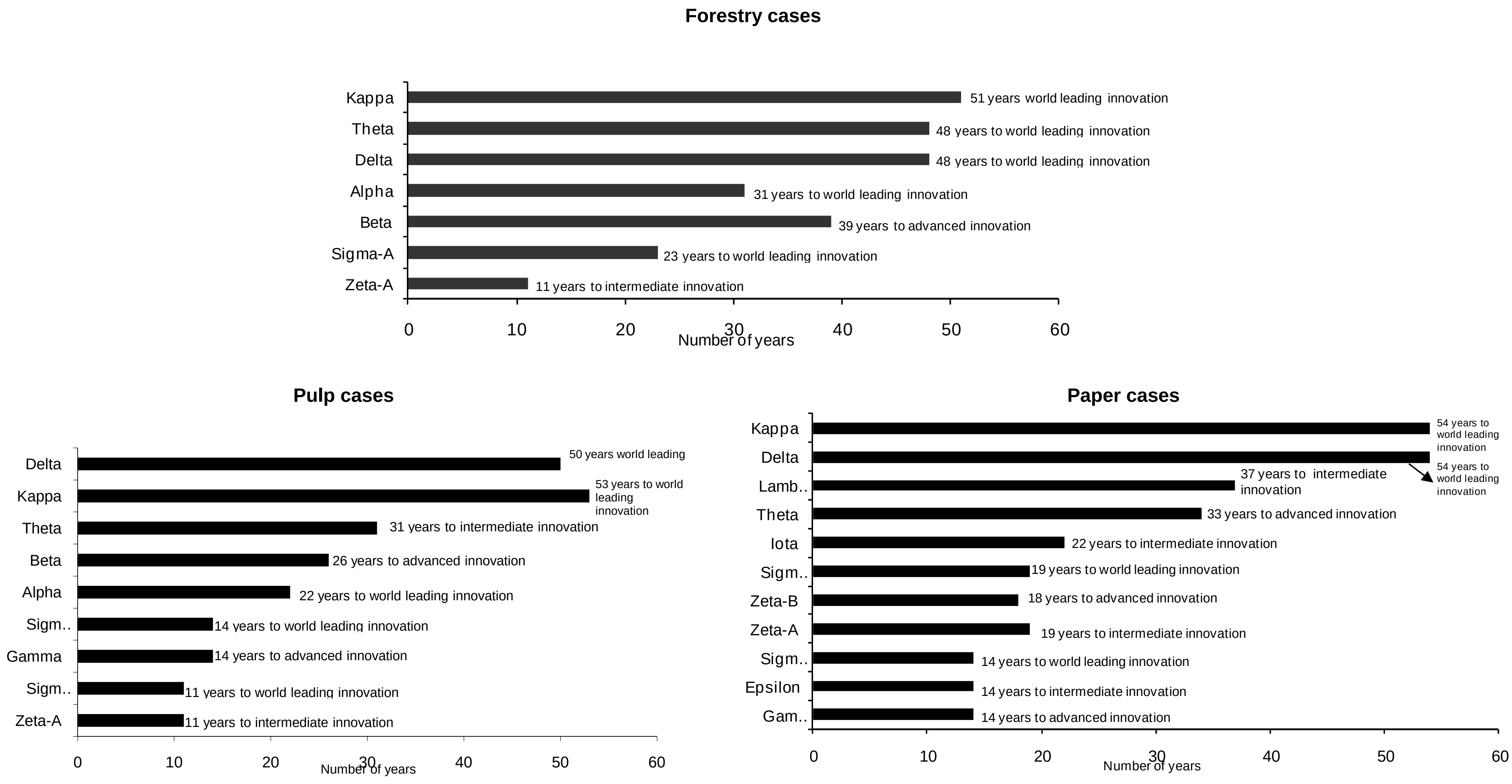
However, several other cases reflect the existence of inconsistencies and discontinuities both *across* and *within* firms in their capability building. For instance, the forestry and pulp-making firms Alpha and Beta started up at almost the same time and began to build up their innovation capability early on. However, while Alpha attained world leading levels of innovation capability in forestry and pulp, Beta's capability levels remained at the advanced level (near the frontier) for forestry and pulp.

The pathways of other firms reflect "breaks" in the accumulation of innovation capability, as will be indicated in Figures 2 and 3 (see next sub-section). For example, the large paper maker Epsilon began by using an entrepreneurial and innovative management style in the early 1900s. In 1925, this firm implemented the production of chemical sulphite pulp from its own pine forests. In 1927, Epsilon pioneered the production of tissue paper in Brazil. In the late 1940s, its innovative behaviour also enabled the production of high-performance tissue paper from eucalyptus, and as early as 1950 it engaged in pioneering research in order to obtain improved bleached pulp from eucalyptus. By the early 2000s, however, the process of its accumulation of innovation capability had not moved beyond the intermediate level. Epsilon had halted its innovation efforts by the early 1990s. The evidence from the fieldwork suggests that in Epsilon's case, micro-level inconsistencies were inherent in its innovation strategy, in line with Dutrénit's (2000) truncation perspective, and its weakened entrepreneurial values were in line with Leonard-Barton's (1995) flip side of innovation capability.

5.2 Speeds of accumulation of innovation capability in the focal cases

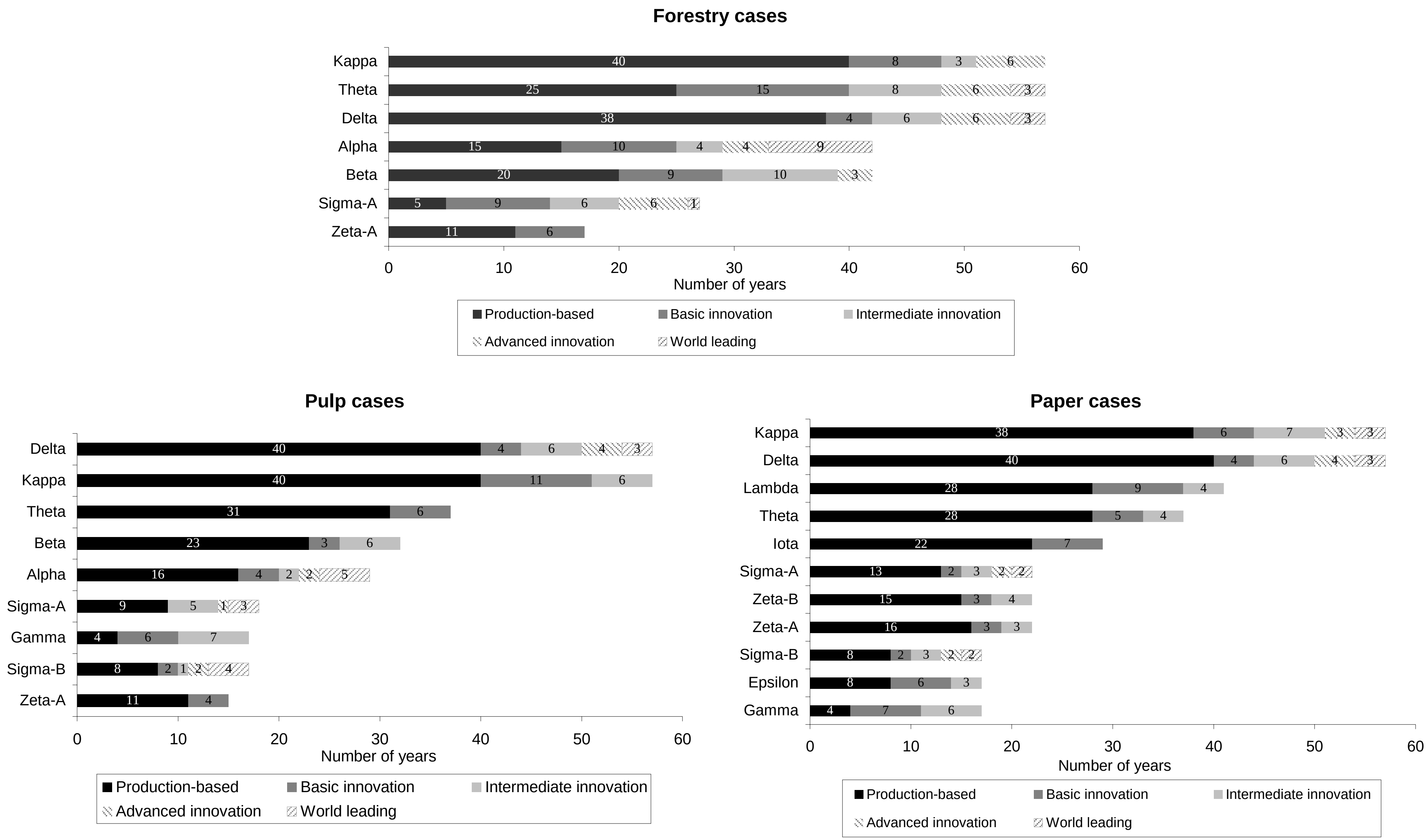
Drawing on previous research (Ariffin, 2000; Figueiredo, 2003), the speed of capability development is defined here as the time (in years) a firm takes to reach a specific capability level. Although the building of innovation capability is a slow process (Bell, 2006), the evidence here indicates that the process of accumulation of capability up to advanced and world leading levels (see Appendix) has been characterised by highly varied time scales (see Figure 2). Some firms took 26 - 33 years to achieve a world leading capability level, whereas others took 50 - 57 years to achieve the same level. Figure 3, on the other hand, indicates that some firms remained stuck for a long time at one level of production capability before building up their innovation capability.

Figure 2. Time taken by each firm to reach their highest capability level during their lifetimes (aggregate capability level)



Source: Derived from the empirical study.

Figure 3. Average time for which each firm remained (or still remains) at particular capability levels during their lifetime (aggregate capability level)



Source: Derived from the empirical study.

Those pulp and paper-based firms that were 17-30 years old were much faster than those over the age of 50 in terms of the rate at which they moved from the level of production capability to the level of advanced innovation capability ($p < 0.05$). In addition, firms aged 31-50 took about 19 fewer years than firms aged over 50 to move from the level of basic innovation capability to the level of advanced capability ($p < 0.05$). Some exceptions to this were apparent, however. Alpha is 10 years older than Sigma-A, and both firms have accumulated world leading capabilities. However, the time taken by Alpha to reach that capability level corresponded to 79 percent of its lifetime, in comparison with 96 percent of Sigma-A's.

There also was high degree of variability *across* the forestry, pulp and paper segments of specific firms. For example, while Alpha and Sigma-A took 31 and 23 years respectively to reach the world leading capability level in forestry and 22 and 14 years respectively to reach the same capability level in pulp, Delta took around 50 years to reach this level of innovation capability in these two segments. Specifically, Alpha (forestry-pulp integrated) took 31 years to achieve a level of world leading innovation capability in forestry and 22 years to achieve that capability level in the pulp segment. Similarly, Sigma-A (forestry-pulp-paper integrated) took 23 years to achieve a world leading capability level in the forestry segment, but 13-15 in pulp and around 20 years in paper. As discussed in Section 5.3, it appears that the efforts of Alpha and Sigma to build research-based innovation capability in forestry (upstream) early on have contributed to a subsequent acceleration in building their innovation capability in pulp (downstream). However, the firm Delta (forestry-pulp-paper integrated) took around 50 years to achieve a world leading capability level in forestry and more than 50 years to achieve the same level in the pulp and paper segments. Also slow, but innovative, was Kappa, which took 51 and 57 years to reach the advanced capability level in forestry and pulp, respectively, and 54 years to achieve world leading capability in paper.

5.3 Timeline of the case-study firms' discontinuous innovation capability accumulation

This section draws on qualitative evidence to scrutinise the evolution of firms' accumulation of capability and innovative performance in four different periods: 1950s-1960s and 1970s-1980s (Sections 5.3.1 and 5.3.2, respectively) and 1990s and 2000s (Sections 5.3.3 and 5.3.4). It will be shown that during the 1950s-1980s, most of their innovative efforts were centred on the upstream forestry segments. Significant innovative activities in pulp and paper-making processes only appeared in the early 1990s.

5.3.1 Organising for innovation during the 1950s-1960s

The period 1950-1969 was marked by Brazilian government and firm efforts to build initial institutional knowledge bases that permitted firms to diverge from the established technological trajectory in subsequent decades. One measure saw the formation of institutional frameworks that were tasked with designing policies to stimulate the technological development of forestry, pulp and paper firms. These also involved the building of government-led research facilities and research funding arrangements that were crucial to complement the build-up of firms' innovation capability. Where firms lacked any research capabilities, an external and collective R&D arrangement was built up using the interaction between firms and government-funded education and research organisations. Another measure saw some firms being engaged in the build-up of their own research-based innovation capability. These efforts at intra-firm capability building were crucial for absorbing the knowledge generated via interactions with external R&D institutions located both in Brazil and overseas. These findings are in line with the conditions for interdependency in firms' efforts in capability building (see Mowery (1983), Bell (1993), and Bell and Pavitt (1993)).

From the mid 1960s onwards, the National Bank for Economic and Social Development (BNDES)[9] made its funding for the pulp and paper industries conditional on the supply of wood being derived from planted forests. However, there were some critical hurdles to overcome. Until the early 1960s, knowledge of silviculture in Brazil was somewhat limited and firms lacked the research capabilities in forestry required to achieve sustainable large-scale pulp and paper production using eucalyptus. In order to overcome such obstacles, a series of initiatives was introduced as described below.

From the mid-1950s onwards, Kappa engaged in systematic experiments on the use of eucalyptus for large-scale pulp and paper production. Although some foreign laboratories were already producing eucalyptus pulp, the existing scientific literature still classified such raw material as being unsuitable for printing and the manufacture of office paper. The son of Kappa's owner undertook a research project to challenge these

[9] Created in 1952 as the BNDE (National Bank for Economic Development), it became Brazil's first institution dedicated to the long-term funding of infrastructure and industrial development.

findings. Although the results of his initial experiments were fruitless, he persisted with his investigations in the laboratories of Florida University at Gainsville in the USA between 1955 and 1962. In the sixth year, his research eventually confirmed that it was indeed possible to obtain good quality paper using 100 percent eucalyptus pulp, and in 1962 Kappa began to manufacture the new product. Despite these and other efforts made by firms, there was very little capability in Brazil to undertake more sophisticated forestry research.

Responding to such industrial needs, in the early 1960s the College of Agriculture at the University of São Paulo (Esalq) began to offer degree courses in forestry (from undergraduate to PhD). It enlarged its postgraduate programmes with the support of government agencies for the provision of studentships and laboratories for the experimental production of pulp and paper. The national providers of scholarships included government bodies like the National Council for Scientific and Technological Development (CNPq) and the Brazilian postgraduate agency (Capes). Funding for the building of laboratories came from the state government.

During the early 1960s, some companies began to demand studies from Esalq with the aim of speeding up the development of their forestry activities. A meeting took place in October 1967 that involved 13 firms, Esalq and the Brazilian Institute of Forestry Development, which generated guidelines for a research programme on forestry improvement. In December 1967, a meeting took place of 18 firms that led to the creation of the Forestry Science and Research Institute (known as IPEF). Its initial focus was to undertake research in the use of high-quality and cost-effective raw materials in Brazil's pulp and paper industries. The associated firms defined the research lines of IPEF to meet their own needs. The main research aim centred on the increase in the productivity of eucalyptus, which was around 24 m^3/ha/year by 1968. This was pursued via a search for new species of seeds.

In 1968, the national seed development programme, which until then fell under the São Paulo Railways Company (Fepasa), was transferred to IPEF. This move enabled the use of the results of Fepasa's previous research on its own vegetative propagation programme using seeds of different Eucalyptus species, including *E. urophylla.* In that same year, in response to concerns about the genetic and physiological quality of existing seeds, two companies sponsored the visit of a renowned researcher from the Australia National University in Canberra to review IPEF's research methods. His recommendations led IPEF to search for new species (e.g. *E. grandis*) that were better suited to the local pulp and paper industries and that used less hybridisation, which was a cause of high variability.

By the late 1960s, following the initiative of 12 entrepreneurs, the emergence of Alpha represented a decisive thrust for commercial success following the eucalyptus-based technological trajectory. Alpha began its Eucalyptus plantation programme in the South Eastern state of Espírito Santo in 1967. Initially, Alpha considered *E. grandis*, *E. Saligna*, *E. urophylla* and *E. Alba* to be the most suitable species to use. Alpha's forestry segment had been built up with eucalyptus plantations using seeds produced by Fepasa, where early experiments had been carried out during the 1920s and 1930s. However, Alpha's forestry activities were marred by uncontrolled hybridisation and high variability in growth rates, stem forms, and wood properties. These problems reflected the poor quality of the seeds and the unreliability of their sources. *E. Saligna* was susceptible to trunk rot, while *E. Alba* showed variations in its physical or biochemical characteristics (phenotypical). The average productivity of both species was no higher than 22 m^3/ha/year. These problems prompted a move by Alpha away from vegetative propagation using seeds, to tree improvement and clonal programmes (see Campinhos (1999), and Evans and Turnbull (2004)). In order to tackle these problems in a more systematic manner, in 1968 Alpha set up its own forestry research centre.

5.3.2 Making the qualitative discontinuity in the technological trajectory: the 1970s-1980s

The period 1970-1989 was marked by innovations in clonal forestry such as the use of macro- and micro-cuttings, tissue culture and clonal deployment.[10] Firms like Alpha took the lead in introducing new techniques of vegetative propagation. By 1970 the number of firms organised under IPEF had increased from 18 to 29. In 1976 there were 388 projects being managed by dedicated teams of engineers and researchers to meet the firms' demands. In conjunction with the firms, IPEF developed organisational arrangements that sought to integrate the technological activities of IPEF and the firms, as described by one researcher:

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[10] Clonal plantation offers a number of advantages compared with the use of seedlings (Evans and Turnbull, 2004): (i) It enables the genetic gains from selection and breeding to be captured quickly; (ii) it is a cost effective way of using hybrids (e.g. *Eucalyptus Urophylla* x *E. Grandis*); (iii) it permits the easier use of desirable characteristics such as pulp yields and disease resistance; and (iv) it produces a uniform material for use in the production process.

> "During the 1970s our aim was to advance research demanded by companies and transform our findings into inputs to enable them to improve their processes and final products. Throughout each year we had several formal and informal meetings, technical visits (on both sides) and joint field days. Hundreds of professionals from the companies participated in these activities. Within each company there were supporting facilities to enable the groups to conduct experiments and test them in the production areas."

These kinds of organisational arrangements became known as the "IPEF model" and were emulated by other organisations involved in forestry research in Brazil. By the mid 1970s, IPEF's efforts, led by the researchers F. Poggiani and W. Suiter Filho in association with firms, pioneered the development of a *rooted cutting technology (macro-cutting)*. Although not a radical innovation, the advances they made involved the control of critical factors that increased the rooting rates. By building on these advances, the researcher E. Campinhos Jr. from the firm Alpha led a research project in the late 1970s that permitted the mass production of clonally propagated plantations of eucalyptus pulpwood in areas considered to be marred by difficult rooting conditions, namely the coastal area of South Eastern Brazil where Alpha and other firms were located.

Further ground-breaking studies led by the researchers A. Borba and A. Brune, and also E. Campinhos and Y. Ikemori, achieved successful rooting results under controlled conditions (i.e. ex vitro or indoor clonal hedges). This method allows the in vitro stage to be left out. The ex vitro method is desirable, firstly because of the reduction in cost in terms of labour and infra-structure, but mainly as a result of the high-quality of the micro-propagated plantlets. These research achievements paved the way for successful intensive clonal *Eucalyptus* forestry in Brazil.

Experiments on the cloning of *Eucalyptus* using rooted cuttings from mature trees had been previously carried out in Morroco (mid 1950s) and advances for their commercial use were made in the Republic of Congo (late 1960s). However, it was not until the early 1970s, mainly within the Brazilian firm Alpha, that new methods were developed for use in large-scale cloned forests for pulp production at an industrial scale (see Poggianni and Suiter Filho (1974), and Evans and Turnbull (2004)). Thus, from a Schumpeterian perspective (Schumpeter, 1934; Kleine and Rosenberg, 1986; Teece, 2007), the Brazilian firms innovated by *combining and putting together* new kinds of knowledge in order to achieve a new kind of commercially feasible raw material for pulp and paper production at a large scale, at a high quality and at a lower cost.

From the early 1970s onwards, by drawing on these studies and combining them with its in-house research, Alpha began to perfect its own genetic improvement programme using clonal forestry to increase the productivity of its eucalyptus pulpwood plantations. Using a combination of strategies of sexual and asexual propagation, Alpha's research indicated that gains in both production volume and wood quality could be achieved using hybrid clones (e.g. *E. grandis* x *E. urophylla*).[11] In 1979 Alpha decided gradually to substitute its plantations derived from seeds with those derived from clonal plantations. The use of cloning enabled Alpha to use the results of its selection and breeding programmes.

Alpha initially selected 5,000 trees from a 36,000 ha plantation, of which 150 clones were identified as being potentially suitable. Only 31 of the very best trees were used in the plantation programme. By 1980, Alpha's first commercial clonal plantation had been established on 1,000 ha; by 1989 this area had been enlarged to 15,000 ha. By 1987, Alpha's annual production of cuttings was 16.8 million. As a result of this cloning strategy, Alpha's eucalyptus productivity increased from 30 to 45 m^3/ha/year (see also Ikemori (1990), and Evans and Turnbull (2004)). These and other genetic improvements had an economic impact on the pulp-making process. It has been estimated that an increase in wood chip density from 0.155 Kg/l to 0.165 Kg/l results in a productivity gain of around US$ 3 million per year for a mill with an output of 300,000 tonnes per year (De Assis, 2001).

Alpha pioneered the introduction of the stem-cutting of rootings at an industrial scale. It was able to propagate clones that were resistant to a fungus that was feared because it caused canker in eucalyptus plantations. In 1984, nearly 17 years after starting its research activities, Alpha achieved international recognition by being awarded the Marcus Wallenberg Prize from Sweden.[12] The mass production of clonally propagated planting stock became more widely distributed in other firms in Brazil (e.g. by the late 1980s, Delta's production of cuttings was 10 million/year).

However, the technology of stem-cutting of rootings presented its own drawbacks, including an accelerated maturation process that caused the rapid loss of rooting

[11] Sexual propagation involves the exchange of genetic material between two parent trees; in asexual reproduction, the new plants are genetically exact copies or clones of a single parent tree.
[12] Established in 1980 in Sweden, under the Marcus Wallenberg Foundation, this highly respected prize seeks to encourage and stimulate path-breaking scientific achievements that contribute significantly to a broadening of knowledge and to technical development within fields important to the forestry, pulp and paper industries.

predisposition, and alterations to the architecture of the root system that caused root deformation (De Assis, 2001; Evans and Turnbull, 2004). This prompted Alpha to make a further upgrade to its forestry R&D centre, in order to strengthen its links with local universities and to build up its partnerships with cutting-edge international research institutes.[13]

The organisational arrangement that involved IPEF and the firms proved decisive for progress in forestry in Brazil between 1969 and 1975. However, in late 1970s the quantity of seeds produced was not sufficient to meet the growing demand for them. In addition, the industry put pressure on the federal government to tighten the regulations on imported seeds and on the dubious reforestation projects that benefited from federal incentives. As a result, in 1977 the whole institutional framework of the pulp and paper industry was restructured. New inter-organisational arrangements were created to control the quality of seeds and to issue certifications for planted areas.

Created in 1973, the Brazilian Agricultural Research Corporation (Embrapa) took responsibility for the National Programme of Forestry Research, thus incorporating all previous research activity. In 1984, Embrapa established the Working Group for Forestry Genetic Improvement. Its objectives were to issue guidelines for the use of genetic material, to create procedures for experiments and to organise scientific and technical meetings. From the early 1980s onwards, while Embrapa undertook programmes of genetic improvement, IPEF dedicated itself to new research in forestry handling and exploitation for firms after their plantations had reached the stage of cuttings.

By the late 1980s, 20 years after having initiated a programme of forestry research, Brazil had consolidated its position as a major exporter of pulp and paper derived from the innovative use of eucalyptus forestry. The contribution made by external R&D arrangements was declining, however. By the late 1980s some firms realised that, because of their specific forestry characteristics and research needs, they could no longer draw on the collective R&D arrangements of IPEF and Embrapa, and they began to strengthen their own research capabilities. Not all firms followed suit, however, and conversely in 1983 firms like Alpha had already taken the initiative to build its own R&D centre, dedicated to pulp and paper activities. This supplemented the work of the forestry research unit that had been established in the late 1960s. In late 1980s, with

[13] It should be reiterated that the issue of the sources of capability (learning) is beyond the scope of this paper.

the support from BNDES, the creation of Sigma-A and Sigma-B represented another major thrust in expanding research activities in forestry, pulp and paper in Brazil.

5.3.3 Building innovation capability along the new technological trajectory during the 1990s

Alpha, Delta, Sigma-A, Sigma-B, Kappa and Theta (forestry) showed resilience by intensifying their efforts in building innovation capability. Firstly, these firms paid greater attention to building innovation capability in pulp- and paper-making processes and products. These innovations came about following the introduction of changes to the chemical processes and equipment used, in order to incorporate other innovations that had been implemented earlier on in the upstream forestry segment. These changes in turn affected the firms' innovative (and competitive) performance. For example, because of the progress of firms like Alpha, Delta, Sigma-A, and Sigma-B in making genetic improvements in the upstream forestry segment, the wood that was being used in their production processes now required fewer chemicals for pulping and bleaching (e.g. by using wood with a reduced lignin content), and consequently generated less liquid effluent. It has been estimated that there is an annual economic gain of around US$1 million for each percent of lignin reduction in wood for a mill with an annual production of 300,000 tonnes, in the first stage of the pulp making process alone (De Assis, 2001).
Secondly, from the early 1990s onwards, pulp and paper firms realised that in order to secure competitive global market positions, they had to respond pro-actively to growing pressure from regulators and society at large in relation to environmental concerns (see Dalcomuni (1997)). Consequently, intense efforts were made to accumulate environmental innovative capabilities in most of the firms discussed herein. By 1992, Alpha had adopted elementally chlorine-free (ECF) and totally chlorine-free (TCF) technology. This development occurred at the same time in the leading firms in Canada and Scandinavia. However, Alpha went further by creating a variation to the TCF process that used a much lower level of absorbable organic halogens (AOX). This process became known as Alpha chlorine-free (ACF) and was patented by Alpha in 1997. One year later, Sigma-A and Sigma-B also created their own 'green' versions of the TCF process. By 1995, 10 of the 13 firms discussed here had already changed to TCF.

Thirdly, at the same time firms intensified their efforts in accumulating R&D capability in forestry. For example, new techniques for cloning eucalyptus were developed, such as mini- and micro-cutting. Compared to the use of stem-cuttings (macro-cuttings), the rooting of micro- or mini-cuttings improves rooting potential, rooting speed and root system quality, and reduces costs. These technologies are very similar in terms of both concept and operational procedure, the main difference being in the origin of the initial propagules. While micro-cuttings use the apices obtained from micro-propagated plantlets, mini-cutting is achieved by the rooting of auxiliary sprouts from rooted stem-cuttings (see Evans and Turnbull (2004)).

In the early 1990s, the development of micro-cutting technology for eucalyptus contributed significantly to the establishment of systems for the large scale ex vitro production of vegetative propagules. Originally, the system made use of mini-hedges established through rooted mini-cuttings grown in small containers. The idea of hydroponics, an operational indoor system using drip fertigated sand beds, was conceived in Brazil in projects led by researchers like E. Higashi and his colleagues. Later, researchers in Alpha (see Campinhos et al. (1999)) used the same concept in a highly efficient intermittent flooding system, where containers of the mini-stumps were immersed in a nutritive solution in order to achieve fertigation. These systems began to produce about 25,000 propagules of *E. grandis* x *E. Urophylla* hybrids per year.

5.3.4 Building innovation capability along the new technological trajectory in the 2000s

Between 2001 and 2004, Sigma-A, Sigma-B, Kappa and two other firms jointly undertook the large scale ForEST research project (Eucalyptus Genome Sequencing Project Consortium), which was funded by the Research Foundation of the State of São Paulo. By drawing on DNA microarrays and bio-informatics, this project identified about 15,000 genes via the sequencing of approximately 100,000 expressed sequence tags (ESTs). This enabled the development of a technology that permitted the identification of genes involved in the genetic control of wood. This in turn led to improvements in the chemical performance of the pulp- and paper-making processes of those firms that were involved in the project (see also Grattapaglia (2004)).

Another large scale research project, Genolyptus (the Brazilian Network of Eucalyptus Genomics Research) was conducted between 2002 and 2008. This initiative involved 13 firms from the forestry, pulp and paper industries (among them Alpha, Kappa, Beta, Gamma, Delta, Theta, Sigma-A and Sigma-B) and seven universities, under the coordination of Embrapa. This group managed to persuade the Brazilian Ministry of Science and Technology to provide funding for the project. This project was remarkable in the intensity of the efforts made during the field experiments to obtain the complete structure of the phenotypes that was required to study the functions of the genes concerned. In addition, this project made use of a multidisciplinary approach and involved researchers in genetics, biochemistry, molecular biology, breeding, statistics, phyto-pathology, wood technology and industrial process engineering (see Grattapaglia (2004)).

Using a pre-competitive design, this project has advanced the molecular breeding of eucalyptus. By building a suite of genomics, field and information resources it has helped scientists to discover, sequence, map, validate and understand the underlying variations in genes and genomic regions of economic importance in eucalyptus, with a focus on wood and disease resistance and its implications for the pulp and paper industries in Brazil. In so doing, Brazil has become one of the few countries in the world to undertake cutting-edge genomic eucalyptus research by calling on a nationwide network of biotechnologists.

During the 2000s, firms that had higher levels of innovation capability began to pay greater attention to the organisational dimension of capabilities to support their innovation activities, particularly with a view to linking the advances they had previously made in forestry with innovation in their pulp- and paper-making processes. Such efforts were specifically aimed at integrating the design of the biology of trees with the requirements of the production processes and the end users. Organisationally, such efforts involved the reconfiguration of their existing R&D and non-R&D arrangements (e.g. in Alpha, Kappa, Delta, Sigma-A, Sigma B), and the creation of cross-functional, company-wide and inter-disciplinary committees and dedicated teams to promote innovative projects.

In 2002, Sigma-A and Sigma-B reorganised their R&D departments into the Centre for Pulp Technological Development, in order to integrate activities that had previously been carried out separately, namely research, quality and technical assistance. During the interviews it was suggested that by combining these different areas of knowledge, the companies sought to speed up product development in order to improve performance. In 2005 for example, this unit designed software using a complex set of equations to calculate the economic value of a clone, allowing the firm to choose the clone that was most appropriate for specific sites. In 2002, Delta re-configured its research centre following a review of its routines and procedures, documentation and analysis processes. By drawing on its capabilities in biotechnology, in 2005 Delta codeveloped a ‘water-barrier package’ that improved the safety of packed frozen food with Sadia, a large Brazilian exporter of chilled and frozen food. From 2003 until the completion of the fieldwork for this study, Delta had been ranked globally as the first or second most innovative supplier of Tetra-Pak. By 2004, Alpha had obtained nearly 30 patents and by the time the fieldwork began, had a further 17 patents under development and was strengthening its systems of intellectual property.

5.4 Summary of main findings and discussions

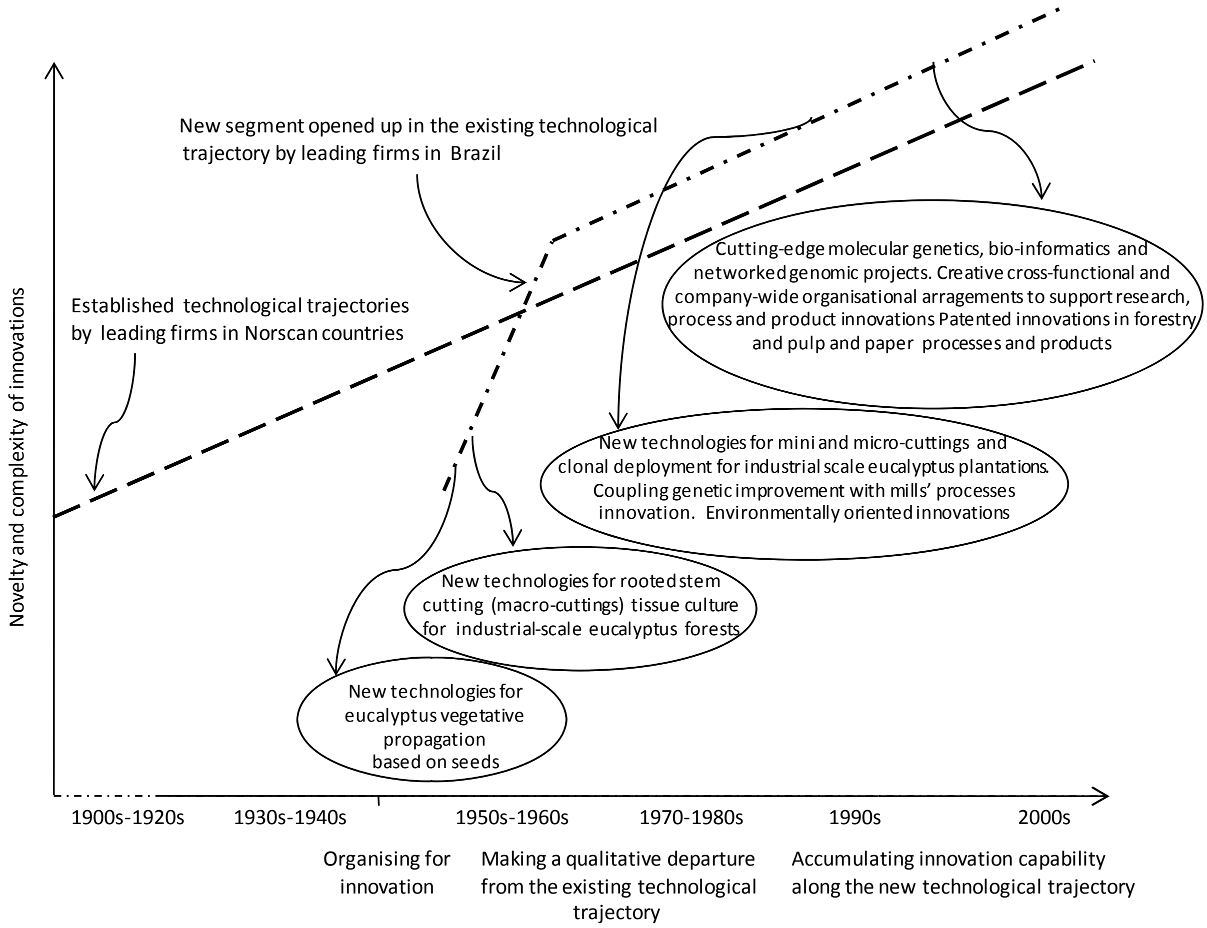
This section that follows is a summary of the main findings and discussions presented in Sections 5.1 to 5.3.

(1) The pathway of the accumulation of innovation capability followed by the firms described herein involved a *qualitative departure* from the established technological trajectory of the global leaders from the Norscan countries. Specifically, the “path-creating” trajectory of the accumulation of innovation capability that has been examined here is typified by firms that have followed *different qualitative directions* of technological development from those previously pursued by the global industrial leaders. Such a deepening of their innovation capabilities does not signify that the firms in question have moved towards a pre-determined technological frontier. Instead, they have rather opened up a new segment in the established technological trajectory, especially in the upstream forestry area. This form of “catch-up” differs from those examined in previous studies (e.g. Hobday (1995), and Kim (1997)), especially from Lim and Lee’s (2001) “path-creating” catch-up. Some of the firms examined here were able to deepen and sustain the accumulation of innovation capability along the new technological segment that they had opened up. Such firms were able to move close to a new innovation frontier or even to become world leading innovators, as represented in Figure 4.

(2) The evidence suggests that by engaging in the eucalyptus-based technological trajectory the Brazilian firms developed a kind of low-end disruptive innovation (see Christensen (1997)). On the basis of the subsequent innovations from the 1970s, bleached eucalyptus, especially from Brazil’s leading firms, has moved from low-end and low-volume market segments to the strong position it holds today supplying high-end segments (Lehtonen, 2005) (see also Section 3). Interviews with industry experts indicated that from the 1990s and especially during the 2000s the price of

eucalyptus has even been higher than price of Norscan countries' softwood.[14] Yet the cost of producing eucalyptus pulp (short fiber) is about 30 per cent lower than the cost for producing Scandinavian long-fiber pulp (Lehtonen, 2005).

Figure 4. Evolution of the eucalyptus-based technological trajectory pursued by Brazil's leading firms



Source: Derived from the empirical study.

(3) As shown in Sections 5.1 to 5.3, however, the process by which firms have proceeded with the accumulation of innovation capability in new directions has been far from linear, smooth or wholly successful, and has instead been marked by a high degree of *variability* in the depth and speed of the accumulation of innovation capability. The pathways followed by all the focal cases can be described in four categories as shown in Figure 5.

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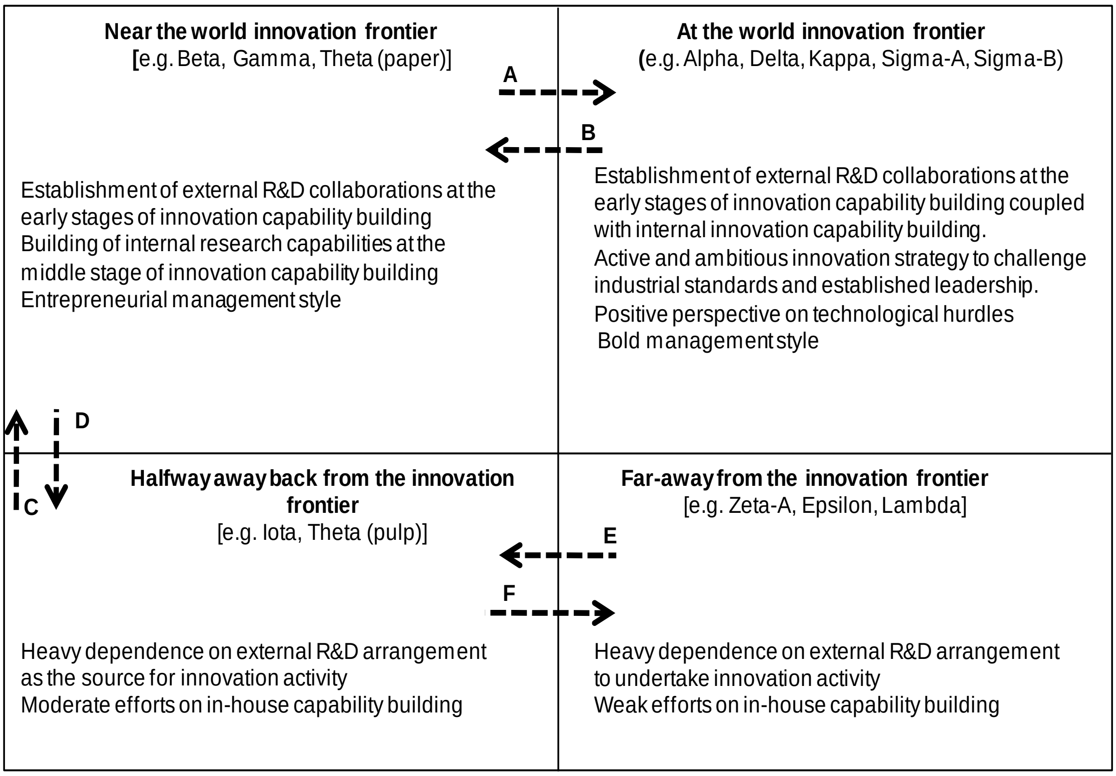
[14] See also World Pulp Monthly – various years.

Figure 5. Types of pathway of capability accumulation in the case studies



Source: Derived from the empirical study.

Those firms that have relied heavily on external sources of R&D between the late 1950s and the early 1980s were not able to improve or sustain their innovative performance through the macro-economic disruptions of the late 1980s and the structural reforms of the early 1990s, despite having entrepreneurial systems of management. However, the firms that exhibited sustained innovative performance throughout such adverse conditions responded pro-actively to government policies (other than protectionism) and engaged in the systematic building and strengthening of their (increasingly internal) accumulation of innovation capability, through their interaction with external R&D arrangements. This finding is in line with those of Mowery (1983), Cohen and Levinthal (1990), Bell (1993), and Bell and Pavitt (1993).

(4) The nature and speed of the firms' capability accumulation towards advanced and world leading innovative performance in new technological segments were also determined partly by intra-firm factors such as the norms and values inherent in their leadership and management style (which are an invisible dimension of their capabilities, see Kim (1997, 1998), and Leonard-Barton (1995)). Their efforts made, risks taken and above all, their perseverance in overcoming constraints were strongly related to a pro-active management style in some of the successful and fast-moving innovators (e.g. Alpha, Sigma-A, Sigma-B), but these qualities were less

clear or even absent in the less successful innovators (e.g. Iota, Zeta-A). However, some firms were led by an entrepreneurial management, but only engaged later on in successful systematic innovation strategies (e.g. the slower innovators Delta and Kappa), while others failed to implement a systematic strategy to build innovation capability (e.g. Zeta-A and Zeta-B). There were also some cases where the firms' pro-activeness in innovation was severely weakened during the early 1990s (e.g. Epsilon). Finally, there was the case of Theta, whose leadership *opted for* prioritising the accumulation of innovation capability in one segment (forestry) over others, notably paper.

(5) Despite the foregoing, there are two caveats for these Brazilian cases. First, it is not possible to determine whether, and to what extent, innovative firms like Alpha, Delpa and Kappa will continue to invest in the R&D required to sustain, deepen and renew their research-based innovation capabilities. These are crucial for maintaining their leading position at the innovation frontier with their competitors from other countries (e.g. Chile, South Africa, and Indonesia). Thus, the sustainability of such leading innovation positions will depend on the firms' innovation strategies and options, as well as the efficacy of industrial policy-making in Brazil. Otherwise, Brazil's leading position could be usurped by other natural resource-rich countries such as Chile, Indonesia, Russia or some African countries. Also endowed with similar natural resources, these countries could themselves engage in intense capability building aimed at achieving international leadership. One challenge is therefore whether, and in what manner, firms that are currently near the frontier will develop into more innovative levels of capability (arrows A, C and F in Figure 5). At the same time, it is crucial to avoid the risk of weakening the existing levels of innovation capability already achieved by the firms. This is an issue of some concern, because although innovation capability may take some time to accumulate, it may deteriorate rapidly in the absence of robust and effective learning strategies (arrows B, D and E in Figure 5). Secondly, even if they continue to undertake efforts in innovation, there is a risk of becoming locked into the same level of innovation capability. One strategic step might be to draw on these innovation capabilities to diversify technologically and/or to continue opening up promising new segments at the ever-changing technological frontier.

6 Conclusions

This paper has sought to examine a kind of “path-creating” trajectory of capability accumulation in natural resource-processing industries. It has done so by drawing on evidence from a variety of case studies using 13 firms from the forestry, pulp and paper industries in Brazil during the period 1950-2007. By building on influential studies of technological catch-up such as Lim and Lee’s (2001), this paper contributes to the expansion of our understanding of the manner in which latecomer firms overtake world leaders (or fail to do so) in terms of capability accumulation and innovative performance in three ways. Firstly, the paper has empirically examined the pathways by which the firms have accumulated innovation capability that have involved a *qualitative departure* from the established technological trajectory at the *early stage* of the development of their capability. This was achieved by interpreting the innovation frontier as a horizon to be explored, rather than an end-point to be reached. In so doing, the discussion has moved beyond the perspective of catch-up using a kind of cumulative continuity along a technological trajectory that was previously developed by the global leaders.

Secondly, this paper has examined the dynamics involved in this kind of capability accumulation. Specifically, the paper has discussed the speeds at which firms have moved (or failed to move) towards progressively more innovative capability levels along the new technological segment that they have carved out. Thirdly, the paper has examined these issues in natural resource-processing industries. In so doing, the paper has shed some empirical light on the kind of firm and government strategies involved in achieving international innovative performance in natural resource-rich countries, especially in Latin America. These findings suggest that the nature of the in-house efforts in accumulating innovative capability conditions the ways in which latecomer firms overcome technological hurdles in their pursuit of significantly new directions at the international technological frontier.

In addition, the paper has explored how the combination of firm-level pro-active innovation strategies and, to some extent, a synergetic relationship with government policies (other than mere protectionism) permits firms to leap the barriers in order to achieve world leading innovative performance. Thus, at least for the firms researched here, these findings have dismissed the thesis of “inherent discontinuity” (Viotti, 2002). On the other hand, the paper has provided some support to the arguments made by Perez (2008) and ECLAC (2008) that a systematic and sustainable accumulation of highly innovative capability in natural resource-based industries could be pursued as a strategy for gaining international leadership in countries like Brazil. However, the paper makes no suggestion that countries like Brazil should pursue a specialist route in natural resources, which would clearly be inconsistent with the diversified nature of its industrial base.

From a methodological perspective, this study has shown how the application of a comprehensive and qualitatively generated measurement of the building of innovation capability, beyond conventional approaches using patent statistics or R&D expenditure, can capture the nuances and dynamics of the process of technological development in latecomer firms. In addition, by using such methodology, the paper provides a contribution to corporate managers and policy makers by systematically tackling the issue of dynamics or timing in the accumulation of technological capability in latecomer firms. As pointed out by Bell (2006), concrete notions about the timing of the accumulation of innovation capability provide a contribution to the understanding and practice of the strategic management of technology and innovation in latecomer firms.

Specifically, analyses substantiated by evidence and based on sound methodology of the time it takes to move from basic to subsequent levels of technological capability in specific sectors, is important for guiding the agenda of investors, governments and companies. For the use of fiscal incentive mechanisms (either generic or coupled with innovation performance), in the presence of foreign competition, the notion of rates of development of technological capability may help governments to set up some approximate time after which companies would have to begin to operate without such kinds of incentives. This could represent a mechanism for discouraging technological sloth.

This paper contains some limitations that could be overcome by further research, however. For example, it has not been possible to gauge how, and the extent to which, *learning processes* have influenced the nature and speed of firms' accumulation of innovation capability. In addition, the paper has not tackled the impacts of capability accumulation (and/or non-accumulation) on the firms' technical, economic, environmental, and social performance indicators. In addition, it would be of interest to understand whether the pathways followed by the firms in their capability accumulation have generated any kind of spill-over in terms of improvements in other areas. Finally, the paper draws on evidence from one country and from firms within one sector. Inter-sector and cross-country national comparative analyses would be beneficial to further our understanding of the nature and speed of the accumulation of innovation capability in firms and industries in developing and emerging economies.

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Appendix. Framework of levels of innovation capability: a condensed version

Levels of capability	*Illustrative Examples*
World leading (Innovation frontier)	Development of models using eco-physiological variables. Clone evaluation, selection and enhancement for seedling production (forest genetics). Development of projects and programs for the improvement of species and soil conditions and biotechnology applications. Strategic management system by performance metric with IT support (process simulation, SAP, supervision system). Intellectual property system. Development of new production processes or phases of processes (e.g. bleaching, ash leaching) using R&D and engineering. Generation and application of mathematical models that support the activities of maintenance. Development of alternative pulps to customised papermaker on the basis of R&D, (integration forest to paper production) working with partnership, university, etc.
Advanced	Development of alternative processes and resources for clonal seedling production and biological diversity protection related to forest ecosystem. Development of processes and resources for evaluation and management of operation impact on soil properties. Project development of impact monitoring and evaluation for forest operation. Development and improvement of mechanical equipment working in partnership with capital goods and engineering and systems firms. Simultaneous support to important customers within a different production segment. Project management for new products and process creation and new equipment implementation in partnership with customer, suppliers and R&D organisation.
Intermediate	Development of resources for forest installation, attendance and recovering and alternative processes and resources for disease and pests control. Project and recovering of degraded permanently protected areas. Improvement of the product characteristics and standardisation by continuous introduction of process automation systems. Introduction and improvement of bleaching pulp processes with elemental chlorine free characteristics. Implementation of technical and management recommendations to adapt the process to the new product characteristic, implementing controls systems that minimise problems in pulp and paper production.
Basic	Assessment of seed quality and features. Monitoring and execution of soil and hydro resources preservation processes. Planning and maintenance of road, railroad and waterway infrastructure. Treatment and control of effluents in forest production areas. Implementation of the general process of chain of custody certification (e.g. FSC) to guarantee that the process uses woods according to sustainable development principles. Identification, planning and control of equipment change following preventive maintenance requirement made by specialist firms (e.g. equipment supplier). Improvement of the product characteristics and standardisation by gradual introduction of process automation systems. Pulp production for special or customised features paper production (e.g. special pulp).

Note: The original frameworks applied during the fieldwork and data analysis involved three individually tailored matrices for forestry, pulp and paper. Each of them identified levels of capabilities for specific functions (e.g. forestry: silvicuture, harvesting, logistics, environmental and social forest management; pulp and paper: project management, process and production organisation, process equipment, and product centred. The adaptation process of each of the frameworks took approximately six months because it involved several consultations with industry experts and company specialists. Qualitative data obtained from the application of these frameworks was transformed into quantitative observations to allow the speed of capability accumulation to be calculated. Such procedures were important to achieve solid construct validity.