Lateral Migration in Resource-Intensive Economies

Technological Learning and Industrial Policy

HSRC
HUMAN SCIENCES RESEARCH COUNCIL

science & technology
Department:
Science and Technology
REPUBLIC OF SOUTH AFRICA

Employment Growth & Development Initiative

RESOURCE-BASED INDUSTRIES

Lateral Migration in Resource-Intensive Economies: Technological Learning and Industrial Policy

February 2006

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Human Sciences Research Council

February 2006

Acknowledgement

The financial assistance of the **Department: Science and Technology South Africa** is gratefully acknowledged.

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February 2006

Chapter 1: Knowledge intensification in resource-based economies, technological learning and industrial policy[1]

1 Introduction

A number of questions that are salient for economic development in South Africa and elsewhere motivate this study.

- Does resource intensity hold back growth?
- Is it possible to reconcile resource intensity with the knowledge economy?
- Which lessons do theory and history hold for economic policy in resource-based economies?

If the answers to these questions were, respectively, "yes", "no", and "none", this study would be bad news indeed. But the answers suggested in this report are no reason for concern. In short, high growth trajectories are possible in countries with intensive resource endowments. In addition, economies can excel contemporaneously in resource extraction and in the creation of the intellectual capital at the heart of the knowledge economy. Finally, new developments in our understanding of the determinants of technological learning, plus what went on in the past in countries as diverse as Argentina, Australia, Costa Rica, the US, or Sweden, do bear lessons for resource-based countries today.

To be sure, resource intensity is not a guarantee for economic development, either. What matters is how resource intensity is being exploited. This study contributes to the discussion in two novel ways. The first is the focus on technological trajectories that start in or around resource-based activities and subsequently become more knowledge intensive. Hence the study traces forward linkages. It thus shows the direct contribution resource-based activities make to the knowledge intensification of the economy at large. In other words, it analyses the co-evolution of resource- and knowledge-intensive modes of production. Much – though not all – of the relevant literature merely looks at the co-existence of the two.

The second is the attempt systematically to compare technological trajectories in an African economy with those in a few Latin American economies. The similarities are obvious. In both regions, the rich natural resource endowments to this day determine what they export. Long episodes in their recent economic history have been marred by low growth in the presence of vast mineral and other riches. Much thinking has gone into probing the reasons for this. But while the Latin American experience has been subject to many comparative case studies, this is much less true for Africa. In addition, many analyses are subject to a didactic bias that contrasts successful

[1] This study benefited from vibrant discussions at a workshop held in early November 2005 in Pretoria. Many thanks are due to participants from near (Miriam Altman, Dunbar Dales, Saliem Fakir, Paul Jourdan, Boni Mehlomakulu, Robert Motanya Magotsi, Adi Paterson, Simon Roberts) and far (Anabel Marin, Victor Prochnik) and, of course, to the chapter authors. The usual disclaimer applies.

examples of catch-up (for example, many East Asian economies in the absence of resource endowments) with failures of underdevelopment (Latin America despite its incredible riches), or resource achievers (for example, Australia or Scandinavia) with resource underachievers (Argentina and Brazil).

By contrast, this study concentrates on countries that are customarily lumped together in the failure category. It analyses examples of technological learning not all of which had necessarily been successful – in terms of their net present value – at the time of writing. Some cases are successful, others are not, and for some it is too early to tell. But they all exemplify technological learning. Since it is possible to learn from mistakes no less than from successes, this study therefore analyses, what works (not), and why, and whether insights from a collection of case studies can inform a broader policy discussion about how best to reconcile the demands of the knowledge economy with intensive resource endowments.

This chapter introduces and summarises the study and sets it in context. Section 2 introduces the problems of resource-based development. It briefly surveys the relevant theoretical literature and combines it with select insights from the economic history of resource-based economies. Section 3 presents data that show that South Africa has had problems in reconciling resource exploitation with more knowledge-intensive, higher-growth activities. It also introduces earlier attempts by South African researchers – mainly associated with Mintek – to conceptualise what they saw as a feasible way out of a dependency on non-renewables in the form of "lateral migration". Together these two sections thus establish the relevance of this kind of research. Section 4 discusses key tenets of technological learning, the role of foreign technology, linkages and interactions, and industrial policy that inform the analysis. Section 5 introduces six incidences of technological learning from four countries – Brazil, Costa Rica, Peru, and South Africa – and presents the methodology. The analysis follows in Section 6 and Section 7 concludes with suggestions for further research.

2 Resource-based development: an update on the resource curse hypothesis

This section first reviews the crude case against resource-based development. It then introduces a more nuanced view based both on theory and historical examples.

The crude case goes as follows. Countries with abundant natural resources are allegedly afflicted by the "resource curse" which says that sitting atop a mountain of, say, gold spoils one's character and for all sorts of reasons stunts one's growth prospects. Adam Smith, for one, is on record for having warned his contemporaries against sinking their investments down mine shafts (1776, 562). In recent times it was Sachs' and Warner's study that attributed low growth performance to resource intensity (1995). International organisations such as UNIDO profess an explicit bias in favour of the secondary sector because it allegedly offers a higher productivity potential and income elasticities than anything the primary sector produces (2005).

Not everybody agrees with this assessment. Smith found his match in heavyweights such as Douglass North (1955) and Jacob Viner (1952) who disputed that there was anything intrinsically inferior in mining iron ore or growing apples as opposed to making toothbrushes. One critique of the influential study by Sachs and Warner

(1995) noted that because its observations fall into a period of debt crisis and structural adjustment that Latin Americans customarily refer to as their "lost decade", it is not obvious that resource intensity was the major culprit of low or negative growth, much less since a comprehensive understanding of what went wrong in Latin America would need to look at political economy issues that have nothing to do with resource intensity as such (Maloney 2002). And newer research (Martin and Mitra 2001) questions the interpretation of the very data that was the basis for Prebisch's (1959) old indictment that secular declines in their terms of trade would militate against the emancipation of Latin America and cement its dependency on the core industrial countries, many of which were – to add insult to injury – former colonial masters. He may have been right for Latin America at that particular historical juncture, but the generalisability of his view to all resource-intensive economies is doubtful.

Whatever people think about the significance of the resource curse, there is agreement that the logic behind it is a combination of bad luck and bad policies. The geological make-up of the earth's land mass and the volatility of commodity prices are a case of bad luck. By definition, bad luck falls outside the ambit of rational policy intervention which is why all one can do is lament destiny's injustice for having been dealt a lousy hand of cards. It is worth pointing out the paradox of associating bad luck with possessing something of value. The resource curse only becomes a valid argument when the lure of, say, gemstones leads to perverse incentives. This brings policy into the picture.

If in reaction to a mineral boom more workers are sent underground to work in the mines and ruin their health instead of using the windfall to invest in education so that their children do not need to follow in their parents' footsteps by pursuing more productive and less hazardous careers, governments can be faulted for having made the wrong decision that favours short-term gains over long-term, sustainable development. Of course, the allure of the rentier economy lies exactly in the luxury of availing oneself of economic policies that in the absence of booming resources would never be sustainable in the first place. To be sure, this is attractive only to the beneficiaries of a predatory state, Mobuto-style, but not to the majority of the population that suffers the consequences of corruption, inequality, and essentially a barren future (Deaton 1999).

Among the better-known facets of the resource curse is the Dutch disease phenomenon. It kicks in when resource booms cause a real exchange rate appreciation that lowers the competitiveness of manufactures and other tradables. If the returns to manufacturing are higher than those available from resource exploitation, or if they could be higher insofar as technological upgrading may cause dynamic efficiencies, then the happy-go-lucky illusion that one can have one's cake and eat it, positively harms development prospects.

Having said this, the resource curse is perplexing for development practice. Surely the solution to the dangers inherent in resource riches cannot be to ignore these endowments, especially if, as in large parts of Africa, they are for the time being the only comparative advantage countries possess (Deaton 1999). The good news is that over the last ten years or so – since Sachs' and Warner's (1995) paper rekindled the debate – theoretical advances and new empirical research significantly improved our understanding of how, and why, resource intensity impacts on economic development.

In short – and this is as intuitive as the resource curse hypothesis was counterintuitive – what counts for growth is not the relative abundance of natural resources in and of itself, but what one does with it (Gylfason 2001b). The often used comparison of resource-rich countries in Africa and Latin America with generally resource-poor but high-growth countries in Asia makes sense insofar as it highlights that countries without natural resources have no choice but to invest in human capital. By contrast, education may seem a waste of time and money in the Lands of Milk and Honey. Hence, resource-rich countries have a larger margin for error for unsustainable economic policies. As countless examples from A(rgentina) to Z(aire) illustrate, this is clearly a blessing in disguise (cf. Gylfason 2001a).

But although the rise in crude prices over the last few years is reason for concern as to whether or not oil-producing countries awash in cash have learnt lessons from history (e.g. Shaxson 2005), it is important to differentiate between success stories and failures. Not all societies with riches under their feet have bitten the dust. It is also important to analyse the transmission channels of the potentially negative effects of resource-based development. For example, natural resources seemingly do contribute positively to growth if one controls for the usual suspects of bad governance, bad policies, and bad institutions (Papyrakis and Gerlagh 2004, see also Neumayer 2004). Put differently, the combination of natural resource abundance, sound macroeconomic policies, and economic policies aimed at generating high savings rates and productive investments, can work very well (Atkinson and Hamilton 2003).

It is certainly easier to explain the uncontroversial successes of resource-based industrialisation with this more open interpretative framework. Thus, the relatively more successful exploitation of mineral resources in the context of economic development in the US compared to Latin America had nothing to do with the quality of those resources that, if anything, were often better in Latin America. The key difference lies in the nature of the learning process that more or less promotes the economic potential of these resources (Wright 2001). What mattered was that the US applied its capabilities from exploration all the way to advanced utilisation in the mineral economy which is why the mineral sector became part of its knowledge economy. Latin America, by contrast, for a long time did not make much of its location-specific knowledge of the resource sector; thus, it was not subject to learning and upgrading (Wright and Czelusta 2004).

A comprehensive analysis of the reasons behind the relative backwardness of many resource-rich economies in different parts of the world would require a historical treatment that is beyond the scope of this study (cf. Landes 1998). A commendable project undertaken by a group of researchers at the World Bank compared the relative failures of Latin American economies with the relative successes of similarly endowed countries such as Australia, Canada, the US, Sweden, and Finland (de Ferranti et al. 2002). In short, it blamed the Spanish and Portuguese colonisers for introducing an anti-progress bias in their dependencies. Hence, initial conditions were anything but ideal. While their contemporaries in other emerging economies were busy building industries, Latin Americans had not yet finished their task of building nations. In addition, the highly unequal distribution of wealth, land, financial capital, and education militated against the establishment of dynamic, innovative societies. Since education was significantly less technically oriented than elsewhere, both active and passive technical capacities were severely compromised. Import-substituting industrialisation thus built on an incomplete and imperfect edifice, and this is an important factor behind many of its spectacular failures (ibid, Chapter 3).

In sum, in the past resource intensity has been less than fortuitously matched with economic development in Latin America than in similarly endowed countries. But a more differentiated picture emerges when looking at the recent history of Latin America. To be sure, the region still has its fair share of basket cases. But it also has very successful examples of economic development across a range of activities that include and go beyond traditional activities: fruits and salmon in Chile, electronics in Costa Rica and Mexico, or tourism in the Caribbean. According to the World Bank report, these experiences have in common that countries exploited their natural resources as well as their locations making use of new technologies and knowledge to improve their production processes. Technology and knowledge may be embodied in foreign direct investment, but it will also be generated by domestic institutions and rely on investments in ICT infrastructure. Ultimately, intelligent policies aided the transformation of natural-resource-based activities into knowledge-intensive assets (ibid, Chapter 4).

Intelligent policies are those that help build the endowments that underlie the knowledge economy – in education and training, support for R&D and innovation, an accessible (ICT) infrastructure, and good institutions more generally (ibid., Chapter 1).

In sum, this brief review of the literature suggests that, first, rich resource endowments may, but need not, slow growth. Hence, for countries with this characteristic, there is no reason to sulk. Second, like other (developing) countries, resource-rich economies must diversify their economies in order to obtain higher and sustainable growth. In this endeavour they face many of the same obstacles that bedevil resource-poor countries, namely the inherent risks and uncertainties of investments in innovative activities that are behind restructuring and productivity growth. The rise of the knowledge economy tends to up the ante on risks and uncertainties. In short, technological, information, and coordination externalities militate against the pursuit of diversification through restructuring by lonely entrepreneurs. This insight motivates interest in industrial policy in general (cf. Rodrik 2004) and more specifically has inspired reflections in Latin America how to move from resource intensity to more knowledge intensive activities (De Ferranti et al. 2002, Ramos 1998).

The major difference between the literature reviewed here and the present study lies in the treatment of traditional factor endowments such as resources and new endowments such as human capital. Much of the literature looks at their co-existence. Perhaps it asks how gains from a resource-based activity can be invested to support the emergence of another activity. That is why in the Costa Rican case we hear a lot about electronics but nothing about coffee – obviously there are no direct linkages between these two activities.

But restructuring and diversification in resource-rich economies are likely to take specific forms insofar as they at least in part happen on the back of related and input industries that supply resource-based sectors with goods and services. Although there is a global knowledge base for mining, agri- and aquaculture, or forestry, specific local circumstances will often ask for specific local solutions. This may mean that the local knowledge base around resource exploitation is deeper than in other parts of the economy. For example, a country with an important share of intensive animal husbandry in the economy would benefit from vets that know about how to keep large numbers of pigs relatively healthy even though they live under unnatural conditions, as opposed to vets who specialise in the psyche of Chihuahuas that do not cope with life in the wrong corner of their owner's couch. Everything else being equal, the depth of knowledge around – upstream and downstream – the resource economy is such that it may spur technological learning that starts in but does stop with a resource-based activity. This insight motivates the interest in the co-evolution of resource- and knowledge-based activities through technological trajectories that link one with the other, and if and how industrial policy may complement it.

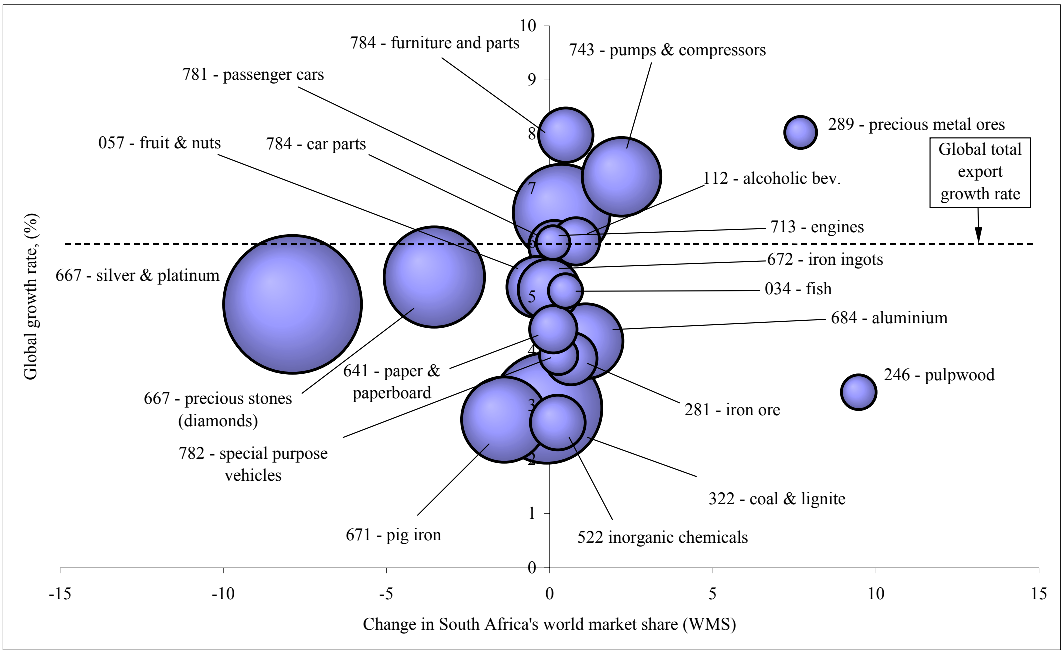
3 Resource intensity and knowledge: old and new economy in South Africa

All is not well with South Africa's knowledge economy. The country's export composition is primarily resource-based and diversification into fast growing export sectors is much less visible than in comparable countries. This is a problem insofar the country's total export growth in the 1990s, at two per cent per annum, lagged that of the world and of similarly endowed countries.2 The main reason for this is the decline in exports of primary products. Consequently, South Africa's overall share of world exports fell from 0.89 per cent in 1988 to 0.52 per cent in 2002 (Edwards and Alves 2005). A similar trend holds for aggregate manufacturing where South Africa's annual growth rate trailed that of developing countries in general and resource-intensive economies as well. This was particularly pronounced in high-technology products.

One way to look at the optimal or otherwise positioning of a country's exports in terms of global demand is to compare its share in those products that account for most of the dynamism in world trade. More precisely, a country is well positioned if its world market share in dynamic products is rising. Put differently, an export specialisation in products with a below average growth rate suggests a suboptimal positioning. Figure 1 shows that South Africa exports relatively few products in which its world market share is rising and which simultaneously record above-average growth. In fact, the top right quadrant is relatively sparsely populated, accounting for only 13 per cent of total exports. By contrast, most exports – 43 per cent of the total – take place in product groups for which world demand is falling (ibid.).

[2] The "resource group" includes 25 economies from Sub-Saharan Africa and Latin America plus Australia, New Zealand, Indonesia, Morocco and Norway.

Figure 1 - The market positioning of South Africa's top 20 exports, 2002



Note: Dotted line is world growth for all products. WMS changes are expressed as percentage points.

Source: Lawrence and Alves (2005, 19)

South Africa is in good company with this not so good performance. The resource group fared similarly (see Figure 2). East Asia's performance, by contrast, is very different (see Figure 3). This analysis does not resuscitate the resource-curse hypothesis in its crude form. But it does show that a high concentration of exports in primary and natural resource-based products was associated with a below-average export growth rate in the 1990s. This is surely one of the reasons that motivated this study in the first place.

The other reason is promoted by analysts associated with South Africa's Mineral Technology Research Council, Mintek. It has found its way into policy discussions, albeit not into the literature. In a nutshell, the argument goes as follows.

Many natural resources are finite. Therefore activities such as mining are ultimately unsustainable. For this reason resource-based economies need to think about a way out, lest they lose their own sustainability. One possibility suggested by the Mintek analysts is to exploit the frequently deep knowledge base associated with sophisticated resource sectors such as mining in South Africa. The knowledge base resides not just in mining proper but also in the capital goods and services sector that developed around it. When these knowledge assets are applied in other sectors that are not linked to resource exploitation, new development trajectories become feasible. The Mintek experts named this process "lateral migration".

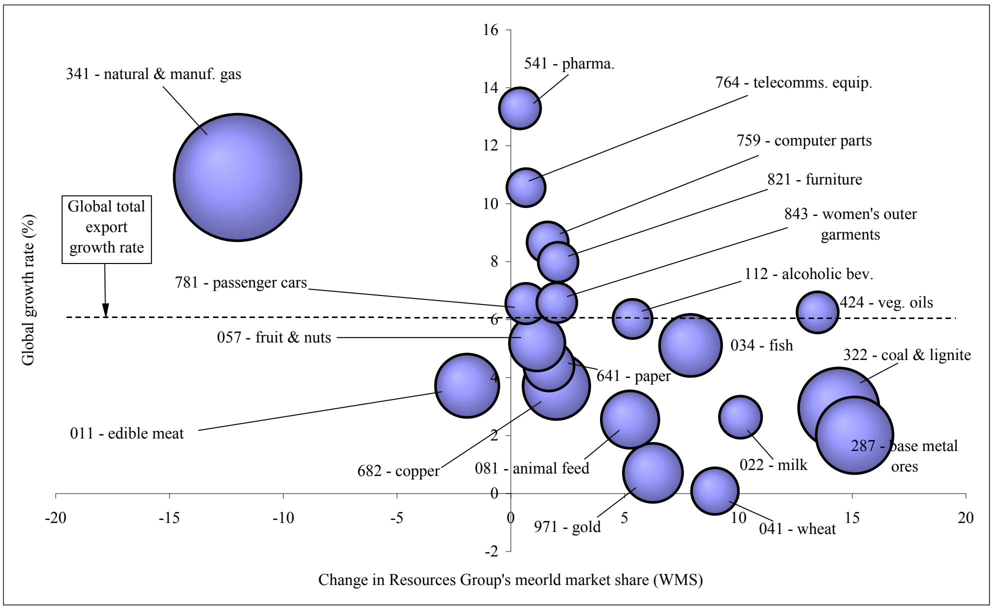
The derivation of the idea of lateral migration is problematic but the concept is nonetheless very interesting. It is problematic because it treats natural resources as a factor fixed by nature. While this is true in the very long run, it is of course not correct that natural wealth is fully exogenous. How much economically useful coal or oil a country has is itself a function of its ability to search for and then extract reserves.

This ability, in turn, depends on the technological capability of the country and especially the concerned sectors. Put differently, what you have depends not just on what lies underground but on how smartly you go about looking for and extracting value from it.

But this should not detract from the important insight associated with lateral migration, namely that resource-based and knowledge-intensive activities may co-evolve. To underline the point, if a country taxes certain old economic activities and provides incentives for perceived new economic activities, resource- and knowledge-intensity may co-exist, but there would be no linkages between the two. Although historical experience shows that select countries have indeed succeeded to create certain competences ex novo, it is obviously easier to think about – and steer – economic development in an evolutionary fashion whereby the accumulation of knowledge is gradual and continuous, and where the challenge hence consists in creating and sustaining linkages that build bridges between the resource and the knowledge economy.

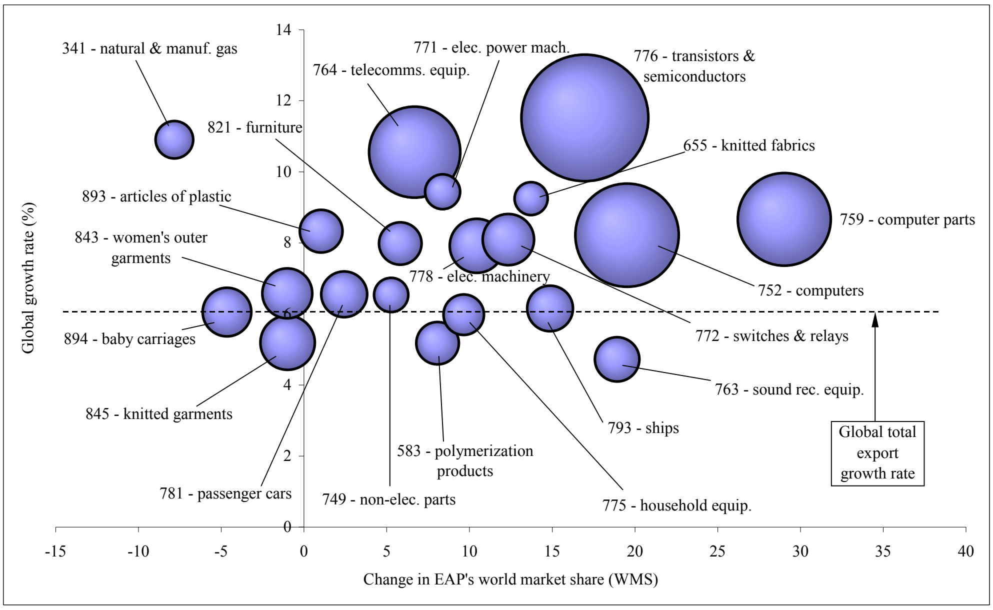
Not all case studies in this report are examples of lateral migration. Some illustrate downstream beneficiation, and others more or less stop with the development of input industries. Not all cases are successful, either, in the sense of fully commercialised technologies; a few are ongoing activities with relatively uncertain outcomes. But they all exemplify co-evolution through linkages. By the same token, they demonstrate how the resource economy can be part of the knowledge economy and vice versa. The strength of the linkages and the relative success of the technological trajectories depend on a series of factors that need systematic analysis. The next section prepares the ground for this.

Figure 2 - Market positioning of the resource group's top 20 exports, 2002



Note and source: see Figure 1.

Figure 3 - Market positioning of East Asia's top 20 exports, 2002



Note and source: see Figure 1.

4 The determinants of knowledge intensification of resource-based activities

The literature on resource-based growth essentially draws on two different but complementary sources. The first is economic history. It explained, for example, how comprehensive mining innovation systems in the US or Australia led to vibrant manufacturing industries. The second is a growing body of economic theory that explains growth and development as a function of a country's ability to learn and build up capabilities through investments in human capital, good institutions, and infrastructure. The best work combines the two in theoretically informed, comparative historical analyses.

This study looks at instances of technology development, both failed and successful, and tries to draw out what made them tick. This leads to insights in their own right and contributes to the literature on knowledge industries based on natural resource-based activities. But insofar this literature is still emerging this study is also partially inductive. It formulates propositions that can be put to further scrutiny in future work. It is the combination of the two that allows making recommendations regarding what policy might do and what it should avoid in contributing to economic diversification based on, but moving away from resource sectors.

In addition to the literature on the resource curse referred to above, four related bodies of knowledge inform this study – absorptive capacities or learning, technology transfer and diffusion, systems of innovation, and industrial policy. First, firms engaged in technological upgrading learn insofar they make use of external knowledge to modify existing or create new technologies. In both cases investments in R&D are important because they help generate new information and because they promote learning. In this perspective, learning is not by-doing but the outcome of a purposeful search for external knowledge to be selected, internalised, and exploited (Cohen and Levinthal 1989, 1990).

Spending on R&D will tend to relate to the characteristics of industry-specific technological and scientific knowledge. The more difficult to assimilate this knowledge, the more firms will spend on R&D. Likewise, the less overlap between a firm's needs and outside knowledge, the more R&D is needed to compensate for the gap through in-house efforts.

Absorptive capacities result not only from R&D (both current and the prior accumulated stock of knowledge) but also as a by-product of manufacturing operations (in the sense that involvement in the latter allows firms to recognise and exploit new information relevant to a product market). They also result from advanced technical training.

Absorptive capacities also influence the level of aspiration of an organisation. Thus, firms with deep absorptive capacities are more likely to recognise emerging technological opportunities. When the knowledge to be exploited is closely related to the firm's existing knowledge base, absorptive capacities can be a by-product of routine activity. By contrast, when that is not the case, it must be created. Finally, absorptive capacities only become "realised" when the assimilated knowledge is commercialised – until then they are merely "potential" (Zahra and George 2002).

Second, insofar the relevant external knowledge is of foreign origin, the key question is how and to what extent technology import and indigenous investments complemented each other (Blomström and Kokko 1998, Lall 1993, Pack and Saggi 1997). On the one hand, with more capable buyers foreign firms have less need to internalise technology transfer through FDI. On the other hand, higher buyer capability also translates into a stronger competitive threat, thus increasing the need for control, especially over the foreign firm's advanced technological assets. It is important to understand if the local firm had the option among a series of technology imports (e.g. license, JV, equity), and if and why it exercised its choice.

Third, learning is embedded in a knowledge infrastructure and takes place in interaction with consumers and producers of knowledge in the private and public sector, including those from outside the country (e.g. Bell and Pavitt 1993, Lall 1993). Thus, once the absorptive capacity of the firm from which the lateral migration technology originates and the nature of the external (foreign) technology input are understood, the focus turns to linkages between case firms and all other actors that matter, in industry, government, academia, and perhaps civil society. The study thus shares with the literature of the national systems of innovation (NSI) a recognition of systemic dynamics and attention to linkages and interactions. But since this study moves from micro to macro, there is no need to describe all institutions that make up the national innovation system (cf. Edquist 1996, Lundvall 1992, Nelson 1993). Instead the focus is on those that matter directly or indirectly (i.e. through skill provision) to the technology at hand.

Finally, innovative activities are subject to externalities that governments may or may not alleviate (e.g. Rodrik 2004, UNIDO 2002). In this instance this refers to specific combinations of investments in science, technology, and innovation on the one hand and requisite policy frameworks on the other that drive innovation and the adoption of technologies.

The reason for drawing on a wide range of literature is not to advance a hotchpotch of theoretical eclecticism. But in order to investigate if there is a pattern to the knowledge intensification of resource-based industries, it is important to understand what internal resources and external knowledge firms draw on, regardless of the purposeful or accidental nature of their technological enquiry. We must also understand the nature and the weight of the contribution of other actors and institutions of the system of innovation to which the firms belong. And finally, we must understand how they individually or collectively overcame disincentives to innovation associated with market failures in technology, information, and coordination. Finally, the analysis of the attendant processes must be embedded in a description of the resource base – including the possible negative impacts it has – from which they took off.

5 Methodology and data

The research is based on six case studies from the two most resource-intensive developing regions in the world, namely Latin America and Africa. Field work took place in the second half of 2005. Each case study team was asked to address a core set of questions in semi-structured interviews (see Table 1). These questions derive from the literature discussed in Section 4 and provide a common framework that allows for systematic comparability.

In the interest of analytical clarity it is important to weigh these groups of questions carefully. A morphological account ending in a conclusion whereby everything is related to everything else does not serve the ultimate aim of this study which is to figure out if there are lessons from these experiences that suggest where and how government might harness the positive aspects while minimising those that are negative. At a minimum, this calls for the differentiation of principal and marginal factors. It was important for case study researchers to construct counterfactual scenarios and have them assessed and triangulated by interviewees with different biases and perspectives on the question at hand.

The case studies are profiled in Table 2. Three originate in agriculture and three in mining. All involve a private-sector firm and many count firms and academic or scientific institutions among their key entities. Some are of rather recent vintage; others go back more than 30 years. Most projects have reached their narrower research objectives but only half have managed to produce commercially viable goods or services. This does not imply that all others are failures; some projects are ongoing and may yet manage to commercialise the object of their endeavours.

The remainder of this section briefly summarises key features of the six cases. It also charts the underlying technological trajectories using the terminology developed by Mintek.

5.1 Sugar-based plastic in Brazil

Brazil is the world's largest producer and exporter of sugar. In response to rising crude prices in the 1970s, Brazil started producing alcohol from its sugar cane for use as a blend in car fuels. Since that time the country has also run a R&D programme aimed at finding alternative sources of alcohol and increasing the efficiency of sugar production, building up substantial expertise in this area. From the late 1990s, a drop in world sugar prices combined with a lower ethanol demand due to lower crude prices plus a gradual liberalisation of the Brazilian economy led to much idle capacity in the industry. This provided the context within which the idea of producing biopolymers was first discussed. Biopolymers help reduce reliance on fossil fuels and also diminish the production of industrial and household waste. They thus have a series of desirable features. Initial discussions involved the Technology Center (CTC) of the sugar and alcohol industry association in the State of São Paolo, COPERSUCAR, the Institute for Technological Research (IPT), a state government-funded research institute, and the Institute of Biomedical Sciences of the University of São Paolo. The partners had previously collaborated in sugar-related research (see Chapter 2 by Velho and Velho, in this report).

Table 1 - Questions for semi-structured interviews

Perspective	Questions
Absorptive capacities or firm learning	▪ Nature of the technology and the resource base from which it originated ▪ Nature of the new application and industry into which the technology migrated ▪ Determinants of cumulative and present absorptive capacities (role of R&D spending, share of R&D spending in turnover over time, advanced technical skills, manufacturing operations (if applicable) ▪ Origin of the LM technology (blue sky, reverse engineering, licensing, involvement in global knowledge flows through scientific or other forms of cooperation, etc.) ▪ Problems with any of the above: nature and cause
The role of foreign technology	Did foreign technology inflows ▪ enhance incentives for innovation ▪ diminish them because they obviated the need for indigenous generation of technology ▪ mattered only in terms of content or also with respect to the transfer mode ▪ benefit from strong/weak IPRs?
Linkages and interactions	▪ What is the nature of the embeddedness of the innovating firm in a system of innovation (suppliers and customers, education and training providers, science institutes, sector associations, public authorities, standard bodies, etc.)? ▪ Which interactions with other firms and with the knowledge infrastructure mattered, and why?
Industrial policy	▪ What sort of market failures did the innovating firm encounter, and how did it (or not) overcome them? ▪ What was the role of industrial policy?

Source: see text.

Funding was available partly through a World Bank loan from its Science and Technology Reform Support Program. The partners agreed to exploit biotechnology in order to produce biodegradable plastics (i.e. polyhydroxyalcanoates) from sugar cane, and registered a patent on the process. Following successful trials, an established sugar mill, Usina da Pedra, agreed to build and run an intermediate-scale pilot unit in an existing mill, and to underwrite the risk of failure. The upshot was total reimbursement of its costs and priority rights to the license for five years should the project succeed.

In 2004, Usina da Pedra opened a commercial plant with an annual capacity of 2000 tons. The product has been tested for a variety of applications, from injection and extrusion technologies to packing materials, cups for seedlings, and medical devices. New specialised research partners joined the consortium, including the Department of Materials of the Federal University of São Carlos, while the bioplastic is given to anyone who wants to test it, including multinational companies such as BASF. Although the consortium managed to produce what can be considered a consistent product with a relatively stable technical specification, bioplastics production is still not cost effective.

Knowledge intensification in this case refers to the diversification in the use of an agricultural commodity toward a variety of industrial applications outside of the food processing chain by way of downstream beneficiation. Thanks to a long tradition in researching alternative uses for sugar, this includes promising applications that move away from the environmentally undesirable use of fossil fuels.

5.2 Biodegradable plastics from maize starch in South Africa

A number of institutes and private companies pursued research on biopolymers in South Africa in the 1990s. This was in part a continuation of work on polymer technology more generally and in part a response to emerging waste management problems due to the ever increasing quantity of plastic bags. In addition, a manufacturer of maize starch was interested in exploring new downstream uses of its products. In the late 1990s these players came together and formed a loose consortium that managed to get government funding from 2002. The research objective was to develop and commercialise a starch-based plastic without the use of significant amounts of synthetic polymers. This case is thus similar to the Brazilian case describe above (see Chapter 3 by Walker and Farisani, in this report).

The consortium reached approximately 80 per cent of its milestones in the third and final year of public co-funding of the project. Although it had failed widely to commercialise a suitable biodegradable plastic from maize starch at an acceptable price, it managed to turn out two products – seedling trays and golf tees – that are commercially available.

This is a case of knowledge intensification because it diversifies the use of an agricultural commodity – from maize for mielies to starch for environmentally friendly plastics – toward a wide range of industrial and household applications, using expertise accumulated from the downstream beneficiation of another commodity, namely oil.

Table 2 - Profile of case studies

Country	Resource base	Lateral migration	Key entities	Period	Results
Brazil	Agriculture	Sugar bagasse ➔ biodegradable plastics	Institute of Technological Research (IPT); Institute of Biomedical Sciences (ICB); Technology Center (CTC) of COPERSUCAR; PHB Industrial S.A. (PHBISA); Department of Materials (DEMa)	1991 – ongoing	PHB production plant within traditional sugar mill; functional but costly biodegradable thermoplastic
Costa Rica	Agriculture	Coffee beans ➔ specialised machinery for sorting by colour of coffee, grains, and seeds	Xeltron; AETEC	1974 – ongoing	Sophisticated machinery using laser technology and artificial intelligence
Peru	Mining	Bioleaching for metal recovery ➔ bioremediation	Minera Lizandro Proaño S.A. (MLPSA); Repadre International Corporation (RIC); Global Environment Emerging Markets Fund (GEEMF); TECSUP; FIMA; Glencor; École de Mines d'Ales; Universidad Particular Cayetano Heredia	1997 – ongoing	Successful conversion of zinc and lead to gold mine but eventual commercial failure; (advanced) research in bioremediation
South Africa	Agriculture	Maize starch ➔ biodegradable plastics	Centre for Polymer Technology, CSIR; Institute of Applied Materials, University of Pretoria; African Products (PTY) Ltd; Xyris Technology CC	2002 – ongoing	Prototypes for future commercialisation: seedling trays and golf tees
South Africa	Mining	Hydro-hydraulic technologies in mining ➔ other sectors ➔ services	Chamber of Mines Research Organisation (COMRO); mining houses	Early 1980s – early 1990s	Hydro-hydraulic technologies used for a variety of applications other than gold and platinum mining; establishment of international consultancies
South Africa	Mining	Coal ➔ medicines	Central Energy Fund (CEF); Enerkom; Department of Pharmacology, University of Pretoria; National Research Foundation (NRF); Secomet; Pfeinsmith	1980s – ongoing	Process patent, product patent on medicinal use of fulvic acid for a variety of applications

Notes to Table 2 -

AETEC is a subsidiary of a US multinational.
COMRO is part of the Chamber of Mines of South Africa (COMSA).
COPERSUCAR is the Cooperative of Sugar and Alcohol producers of the State of São Paolo, the world's largest exporter of sugar.
CSIR = Council for Scientific and Industrial Research, one of South Africa's eight statutory science councils.
DEMa is part of the Federal University of São Carlos.
Enerkom is the research arm of CEF, South Africa's parastatal responsible for managing its fossil resources.
FIMA is an equipment producer.
ICB hosts the Laboratory of Genetics of Microorganisms and Biotechnology and is part of the University of São Paolo Brazil's most prestigious university.
IPT is a public research institute of the State of São Paolo.
MLPSA is a family-owned mining firm.
PHBISA is a partnership between two of Brazil's strongest groups in the sugar and alcohol industry.
RIC and GEEMF are Canadian investment funds.
TECSUP is a mining training centre.

5.3 Bioleaching and bioremediation in Peru

Peru is rich in mineral resources. Together with its Andean Pact neighbours the country was involved in attempts to use bacterial leaching to recover copper in the 1970s. Although successful, these attempts became victims of a deep crisis afflicting the mining sector in the 1980s. Following privatisation and liberalisation of the economy and subsequent inward direct investment by US mining houses, bioleaching took off again in the 1990s. This study describes the technologically successful but commercially unsuccessful indigenous development of a hydro-metallurgic method of gold leaching. A small, family-owned mining firm, Minera Lizandro Proaño S.A. (MLPSA) managed to get private international funding for a project to transform a lead and zinc mine into a gold mine. From 1999, gold was recovered through a cyanide-based technology in connection with the use of bacteria. Two other local actors were involved. A mining training centre (TECSUP) explored the feasibility of using the bacterial leaching technique to treat mining tailings. A domestic equipment producer (FIMA S.A.) was primarily responsible for the construction of the project (see Chapter 4 by Kuramoto and Sagasti, in this report).

The technology was essentially re-engineered from a process owned by South African mining house Gencor which the latter agreed to license albeit at a price too high for the Peruvians. Bottlenecks in mining output meant that the plant's demand of minerals could not be met and saw to it that it had to be closed only a few years after it opened. However, the process of gold and silver extraction per se was successful.

The scientists most closely associated with the experience used the insights gained about the behaviour of bacteria in metal extraction to develop research in the use of bacteria for remediation. Contaminated soils can be remediated using bacteria either by extracting the toxic substances or by reducing their toxicity.

Knowledge intensification thus took place in an input industry; a technology external to Peru was first adapted to local circumstances in mining (bioleaching) and then pursued further for applications that extend beyond mining (bioremediation). Since bioremediation can be applied outside of mining, this case therefore harbours the potential of lateral migration.

5.4 Hydraulic technologies in South Africa's mining sector

Historically South Africa has been a highly resource-intensive economy, particularly with respect to mineral deposits. Mining houses were interested in hydraulic technologies to increase labour productivity in the face of (artificial) labour scarcity and increasingly deep and thus more costly mining operations from the mid-twentieth century. After a long tradition of research in emulsion hydraulic technologies, the research arm of the Chamber of Mines, COMRO, in the early 1980s started research into combined hydraulic power and cooling systems. Hydraulic power systems are advantageous because they are more efficient than pneumatic drills and create much less mechanical and exhaust noise. In turn, water (i.e. pure) hydraulic systems are superior to emulsion (i.e. mixed) hydraulic drills among other things because by definition they do not leak oil into the environment. By the early 1990s, a commercially viable hydro-hydraulic technology existed, making South Africa a world leader in this regard (see Chapter 5 by Pogue and Rampa, in this report).

Engineers associated with the now defunct COMRO have formed successful consultancies specialising on drilling and cooling technologies that operate worldwide. In addition, the technology is being explored as water cutters in the food and steel industries and in aircraft rescue, and has found a few applications outside of the mining sector. Knowledge intensification took place primarily around a supplier industry but, similarly to the Peruvian case introduced above, preliminary evidence of lateral migration exists as well.

5.5 Humic substance research in South Africa

South Africa sits on vast reserves of coal which is its main energy feedstock. Liquefaction of coal plays an important role in local oil supply. In the mid-1980s the Central Energy Fund (CEF), South Africa's state oil agency, mandated its research branch, Enerkom, to look into alternative uses for coal. Enerkom focused on humic substances. They are naturally occurring acids that are good fertilisers and have been used as folk medicine, especially in Asia. Enerkom developed and patented a process by which it extracted humic acid through oxidisation of coal. But the resulting product was too expensive for use in agriculture. Hence it concentrated on researching the medicinal properties in collaboration with the University of Pretoria (see Chapter 6 by Lorentzen, in this report).

The research found that humic acids have anti-microbial, anti-inflammatory, and anti-viral effects. Due to their anti-viral effects, humic substances were used in clinical trials of HIV-positive patients in Tanzania. For a number of reasons, these trials were extremely controversial. The negative publicity they attracted led to the sale of the state-owned company that had been at the forefront of humic substance research, including its intellectual property rights, to an overseas firm. Although some medicinal applications of humic substances have been thoroughly researched, tested, and approved for sale, a twenty-year old research tradition was essentially cut short through the sale of the South African property rights.

In this case the dynamics of the technological trajectory are overshadowed by the complicated politics of HIV/AIDS in South Africa. Nevertheless, lateral migration took place insofar the search for alternative uses of coal gave rise to a research tradition into the medicinal properties of humic substances that eventually substituted a plant-based carbohydrate as the source for the acid.

5.6 Specialised sorting machinery in Costa Rica

Xeltron is a small, specialised machinery manufacturer located in an export-processing zone between San José and Cartago. Xeltron designs and produces machinery that by colour sort coffee, rice, beans, nuts, and seeds in general. Almost all of Xeltron's output is exported. The beginning of the company dates back to the mid-1970s. At that time coffee-sorting machinery was imported, and only maintenance and repair was locally done. Xeltron's founders introduced a number of technological innovations over the years. They first improved on existing colorimetric techniques by employing optical analysers that allowed for much more precise measuring of colour. Subsequent technological upgrades included the use of microprocessors and semiconductors and, finally, artificial intelligence. Xeltron holds five international patents on its innovations (see Chapter 7 by Giuliani, in this report).

This is the only pure case of successful lateral migration. For the country as a whole, it occurred because Xeltron's machinery design took its point of departure in coffee crops, one of Costa Rica's traditional mainstays. For the company, lateral migration moved machinery strictly developed for the sorting of coffee beans to other grains, and finally even the sorting of plastics and emerald products.

5.7 Overview

Altogether the data consist of two cases of downstream beneficiation; two cases of development of input industries each of which is involved in some lateral migration; and two cases of lateral migration proper where the original resource – coal in one case and coffee in the other – is no longer necessary for the application of the technology. Figure 4 provides an overview.

Since the study does not employ a proper measure of knowledge intensity, the relative positioning of the six cases is merely an approximation. Comparisons are possible along either the vertical or the horizontal axis, but not both. Thus, it is evident from the research that the Brazilian endeavour at sugar beneficiation was more knowledge intensive than the South African. Likewise, the South African drill experience led to more lateral migration than the leaching experiment in Peru.

Figure 4 - Knowledge intensification and technological trajectories in the six cases

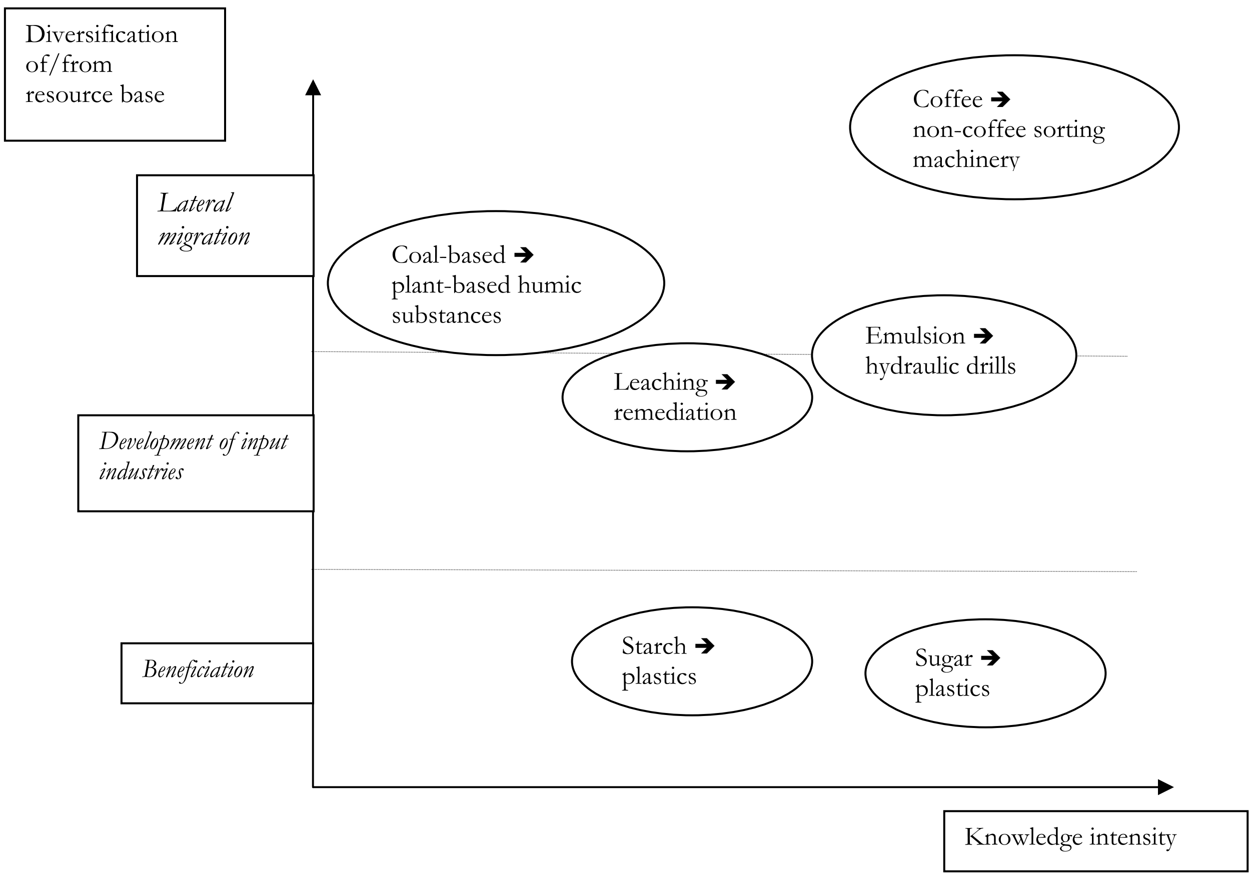


Table 3 - Determinants of lateral migration in six case studies

	Brazil: bioplastics	Costa Rica: sorting machinery	Peru: bioleaching and -remediation	South Africa: biopolymers	South Africa: hydro-hydraulic power and ventilation	South Africa: humic substances
Absorptive capacities	High and rising thanks to consistently high public/private investment in R&D.	High and rising thanks to consistently high R&D investment and internal skill upgrading by firm.	Fragmented and discreet because of inconsistent investment in R&D.	High because of strong tradition in polymer research. Rising thanks to strategic search by science, university, and private sector. Skill upgrading through training in university.	High because of dedicated, long-term research programme. Potentially diminishing because of termination of main research vehicle.	High because of dedicated, long-term research programme and training through university. Potentially diminishing due to interruption in funding.
Foreign technology	None.	Technical expertise enhanced incentives for innovation. IP protection not important for market leadership.	Imports of capital equipment through development assistance enhanced incentives for innovation.	Technical expertise enhanced incentives for innovation. Reliance on license initially positive but then withdrawn.	JVs and other partnerships with MNCs enhanced incentives for innovation. Control of potential abuse of IP protection important for technology diffusion.	None.
Linkages	Intensive interaction between universities, technology centres, and industry.	Poor with domestic suppliers, customers, education institutions. Critical interaction with MNC subsidiary.	Poor, especially with engineering departments in universities.	Intense linkages between science sector, university, and private firms.	Strong linkages within sector between research organisation and private firms.	Strong but isolated linkages between research arm of parastatal and university department, and between university department and private firm.
Industrial policy	Govt. funding key for ethanol-from-sugar and later for channelling World Bank funds to bioplastics consortium.	Mkt failures in infrastructure. Gov. support poor in R&D, trade, marketing. EPZ very bureaucratic.	Andean Pact initiatives in 1970s set up but did not sustain research programme. Strong financial constraints on further research.	Public co-funding relatively bureaucratic to access and small scale.	Mission-oriented research historically important.	Time-inconsistent investment in technological exploration.

Source: see text.

6 Analysis

The case evidence shows the following (see Table 3). In five out of six cases the involved entities had high absorptive capacities thanks to competences accumulated over time. In three cases absorptive capacities were rising due to investment in R&D and the upgrading of advanced technical skills. In the remainder, diminishing or uncertain investments in R&D meant that absorptive capacities might fall. In this respect, bioleaching and bioremediation in Peru appears to be the case where learning is most difficult and technological upgrading perhaps least likely.

Foreign knowledge played no explicit role in two cases and increased incentives for innovation in four. There is no evidence that it was ever perceived as obviating the need for the indigenous generation of knowledge. Hence, foreign technology and local knowledge appear to be complementary.

Linkages and interactions between firms, science institutes, and universities – or a subset thereof – mattered greatly in four cases. Not surprisingly, systemic dynamics are important for knowledge intensification. The exception is Costa Rica where an individual firm managed to compensate for positive dynamics with respect to linkages with the training system or with capable domestic suppliers, respectively, though in-house training and the use of external suppliers. By contrast, neither an individual mining company nor the mining sector as a whole in Peru can overcome the negative consequences of an absence of linkages with the university sector. Likewise, when in South Africa sectoral systemic dynamics were interrupted following the merger of the very focused mining research organisation into a science council with a broader orientation, it would appear that capacity was lost for good. This suggests that linkages are important, and that in their absence individual firms might be able to compensate for the resulting shortcomings in highly specific niches, but entire sectors are unlikely to do so where issues of scale are key.

Industrial policy does not appear to be of great importance in these cases in terms of overcoming information failures. Where firms perceived opportunities, they invested even in the face of relatively high risks. Much more important are the long-term financial constraints that bedevil even promising and partially successful research and development, especially when things do not go exactly according to plan. It appears as though the potential technological merit of those technologies that have not yet been commercialised exceeds the capital available to make this happen. This is a problem. In the Peruvian case, coordination failures seem to be a problem. That, too, could be addressed by interventions aimed at setting up the dynamics of a national system of innovation.

This is not to say that industrial policy played little role in the cases under consideration here. A more nuanced interpretation would distinguish between massive, targeted interventions such as those that brought about Brazil's move into ethanol production from sugar cane, and much smaller subsidies in favour of, for example, research cooperation between science and industry for the development of biopolymers in Brazil or South Africa.

What stands in the way of successful commercialisation in both the latter cases is the relatively high production cost of bioplastics as opposed to synthetic polymers. If either government priced waste management costs into conventional packaging made from synthetic polymers, it would contribute to levelling the playing field between the rival technologies, possibly giving rise to substantially new technological solutions, or knowledge intensification writ large.

The importance of industrial policy may also be related to levels of development. In the middle-income countries under investigation here – Brazil, Costa Rica, and South Africa – absorptive capacities seem the single most important determinant of lateral migration followed by linkages and foreign technologies. In other words, things happen even in the absence of strong industrial policy interventions because firms and research institutes have the wherewithal to internalise external knowledge, often in interaction with other economic actors. However, in Peru where the competences of firms are less strongly developed and where systemic interactions are few and far between, industrial policy might be necessary in order to address the weaknesses that hinder a more fortuitous technological trajectory, namely a deeper commitment to firm learning and the creation of linkages between the productive and the training sector.

7 Conclusions

This study analysed six cases of knowledge intensification in resource-based activities. It relates to and builds on a sizeable body of work on resource-based growth. It tried making an original contribution by accompanying its analysis of firm learning with attention to linkages between what many see as almost separate entities, namely the "old" factor-based economy and the "new" competence-based knowledge industries. For developing countries in particular it is clearly more realistic to make use of prior accumulated knowledge to promote new competences, as opposed to going for blue-sky applications. Hence bridges between old and new are important or, put differently, it is primarily in the co-evolution of human capital, scientific pursuit, technological development, and concomitant infrastructure investment around the linkages that resource-based economic activities can become more knowledge intensive and thus lead to higher growth.

The study confirms that knowledge intensification is a possible answer to the resource curse potentially bedevilling resource-intensive economies. It also shows that such a strategy is not easy. Much has been learned from comparing experiences with resource-based growth from around the world and in different periods of time. Most comparative studies took their lead from success stories and formulated recommendations accordingly. This research took a more agnostic view and compared successful with not so successful cases. Reality is more nuanced than a simple dichotomy of success and failure, and in any event learning can be based on insights of why failures occurred as much as on those from luckier tales.

The crude version of the resource-curse hypothesis has been convincingly rebutted. This was the merit of comparative historical analyses of, say, Australia and Argentina. With determinism off the table, the challenge lies now in systematically linking historical and theoretical insights – namely the potential of resource-based growth and the importance of created assets such as human capital and knowledge infrastructure – to the empirical differentiation of indigenous capabilities across developing countries in the present period. The case analysis undertaken here suggests important differences between a relatively poorer country, Peru, with more advanced economies such as Brazil. This warrants further study. Similarly, much like the process of knowledge intensification is different from sector to sector, perhaps the rather more general attention to, say, R&D subsidies must be analysed with the specifics of what drives innovative activities across different sectors in mind. For example, there are likely important differences in agriculture and mining from which this study abstracted. In sum, a better understanding of the conditions under which knowledge intensification could be a successful strategy of industrial diversification requires a larger sample of cases from a more diverse set of developing countries.

Much heuristic mileage could be gained by raising the systematic requirements of the comparisons. For example, if knowledge intensity were properly measured both in terms of inputs (e.g. R&D investments) and outputs (knowledge assets embodied in the new technology), it would be possible better to understand the efficiency and effectiveness of public policy in support of knowledge industries that originate in or otherwise relate to resource-based activities.

Propositions worth testing include the following. This list is by no means exhaustive. First, absorptive capacities (of the relevant R&D entities) are the single most important determinant of lateral migration. Second, knowledge intensification can take place in the absence of foreign technology and with weak systemic interactions, but only from a certain level of economic development (in other word there is a threshold value of absorptive capacities). Third, the import of industrial policy is proportional to the level of development and the level of ambition behind promoting knowledge industries. Ceteris paribus, at lower levels of economic development (of countries) or technological maturity (of sectors), industrial policy is needed to bring about a minimum degree of absorptive capacities. In addition it may have to secure access to external knowledge and incentivate linkages and interactions. Likewise, the higher the ambition behind the policy, the more necessary it becomes to align the R&D endeavour with the requisite regulatory changes to facilitate the emergence of technological opportunities.

Many more insights are available in the case studies that follow.

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The development of a sugar-based plastic in Brazil

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February 2006

Chapter 2: The development of a sugar-based plastic in Brazil

Abstract

Is there an inescapable dilemma between exploiting natural resources and becoming knowledge-intensive? This article presents a case study that provides evidence that natural resource-based activities can be knowledge industries. The case in question is the establishment of an industrial plant to manufacture biodegradable plastic from sugar in Brazil. This development is closely associated with the long term activity of sugar and alcohol production in Brazil, which is based on the natural endowments of soil, climate and geographical extension that favors sugar cane cultivation. This notwithstanding, the emergence of the bioplastic industry was only possible because of a specific government scheme to build research capacity and knowledge production in biotechnology which also stimulated cooperation between the public and the private sector. Therefore, the most important lesson from the case seems to be that there is a key role to be played by public policies, and more specifically by S&T policy, if natural resources rich countries want to upgrade their related technological activities.

Acronyms

BNDES	National Bank for the Economic and Social Development
COPERSUCAR	Cooperative of Sugar and Alcohol Producers of the State of São Paulo
CTC	Technology Center Copersucar
DEMa/UFSCar	Department of Materials of the Federal University of São Carlos
EMBRAPA	Brazilian Corporation for Agricultural Research
IAC	Agricultural Institute of Campinas
ICB/USP	Institute of Biomedical Sciences of the University of São Paulo
INPI	National Institute of Intellectual Property
IPT	Institute for Technological Research
PADCT	Science and Technology Reform Support Program
PDE	Research, Development and Engineering
PHB-HV	Polyhydroxybutyrate/valerate
PHBISA	PHB Industrial
PLANALSUCAR	National Program for the Breeding of Sugar Cane
Proalcool	National Programa of Ethanol
SBIO	Biotechnology sub-program
USDA	United States Department of Agriculture

1 Introduction

It is common sense these days to say that countries must become "knowledge economies" if they want to participate in any meaningful way in the global market. However, despite earlier predictions that Latin American countries would follow the Asian manufacturing successes, evidence shows that the former´s rich natural resource endowments are still determining what they export. This is the case even for the most industrialized Latin American countries, including Brazil. In such circumstances it is highly relevant to ask whether that continued specialization in natural resources will leave Latin America behind in the slower "old" economy.

This article attempts to address the above question by analyzing a case that shows that there is not an inescapable dilemma between exploiting natural resources and becoming knowledge-intensive. The case is an example that natural resource-based activities can indeed be knowledge industries. The argument is that for this to happen it is necessary an enabling environment in which public policy plays an essential role. Policy actions include macro-economic and industrial policies that affect directly or indirectly the exploitation of natural resources and the industries associated to it, but more specifically S&T policies. The latter are crucial to create human capital as well as the linkages between private firms, government research institutions and universities.

The case in question is the establishment of an industrial plant to manufacture biodegradable plastic from sugar in Brazil. This development is closely associated with the long term activity of sugar and alcohol production in Brazil, which is based on the natural endowments of soil, climate and geographical extension that favors sugar cane cultivation. This notwithstanding, the emergence of the bioplastic industry was only possible because of a specific government scheme to build research capacity and knowledge production in biotechnology which also stimulated cooperation between the public and the private sector.

In order to tell this story and develop the argument, it is necessary first to set the scene. Thus, the historic context which created the conditions and the motivations for the development of the biodegradable sugar-based plastic is presented in Section 2. This is followed by an account of the R&D project that originated the industry in question, highlighting the role of the various actors and the relations between them (Section 3). Section 4 then provides a description of the technological process for obtaining a sugar-based plastic that was developed by the R&D project, transferred, scaled up and adopted by the industry.

The last three sections focus on specific aspects of the development of the bioplastic. Section 5 provides data on the financial dimension of the project and Section 6 on the outputs generated in order to illustrate the impact of the project on research capacity building and knowledge production. A summary of the key features of the project is provided in Section 7. The concluding section that closes the article points out the main findings relevant for the argument.

2 The context and the motivation of the research project for the development of a biodegradable sugar-based plastic

Brazil is the world's largest producer and exporter of sugar. From its sugar cane, Brazil produces not only raw and refined sugar but also anhydrous and hydrous alcohol mainly used as a blend in domestically-consumed gasoline. During the last quarter of the past century the expansion in sugarcane production and processing in the country has been astonishing and was driven by different factors. Starting in the mid 70's, the ethanol program (PROALCOOL)[3] increased the production of that fuel 30 fold, a process that occurred in two phases. Firstly by expanding the crushing capacity of the already existing sugar mills with adjacent distilleries and secondly by building new autonomous plants, dedicated only to the production of ethanol.[4] Sugar cane producers were quick to respond to the demands created by PROALCOOL. Credit guarantees and low-fixed interest-rate subsidies were provided for the construction of distilleries as well as for purchasing land. Moreover, in 1979, the price of hydrous-alcohol-powered vehicles was set at 65 percent of the equivalent price for gasoline-powered vehicles and taxes for these vehicles were also set below those for gasoline-powered vehicles, thus stimulating alcohol production. Furthermore, gas stations were allowed to supply alcohol for alcohol-powered vehicles all weekend, whereas gas stations were closed for gasoline-powered vehicles on the weekend. Petrobras, the state oil company, controlled ethanol distribution. As a result, the production of ethanol alone jumped from 0.55 to 15.3 million of cubic meters between 1975 and 2004. Growth of sugar cane production followed suit increasing from 64 million ton/year in 1975 to 350 million ton/year in 2004.[5]

Brazil has now an installed capacity of sugar cane processing of 360 million tons per year, crushed in 320 mills concentrated in two distinctive production areas, comprising approximately 5 million hectares of land.[6] The Center-South region is characterized by highly productive soil and excellent growing conditions and is one of the lowest cost growing areas in the world, estimated at 5 to 5.5 USD cents per pound. This region concentrates 85% of the Brazilian production, which is harvested and processed from May to November. The North-Northeast region produces the remaining 15%, which is harvested and processed from December to July, and is characterized by generally low yields and high costs due to periodic drought and poor soil. Nowadays Brazil

[3] Although the primary cause for the development of PROALCOOL was the sharp increase in petroleum prices in 1973 and the country's heavy dependency on imported crude oil, another impetus was the collapse of sugar prices on the world market in November 1974. With the creation of PROALCOOL, sugar was transformed into alcohol, strengthening the options for its use. Response to the stimulus of the program came primarily from the sugar producers, who undertook rapid construction of adjacent distilleries to use the surplus of sugar cane.

[4] Adjacent distilleries are those built alongside a sugar mill and use all the existing structure and facilities. They can process either residual molasses from the production of sugar or cane juice. The autonomous distilleries are those built exclusively to produce ethanol from sugar cane juice.

[5] Negrão 2005 (personal communication).

[6] Brazil has about 320 million hectares of land suitable for cultivation and only 53 million are under production. Sugarcane accounts only for about 5 million hectares or less than 10% of the total cultivated area. Sugarcane area is considerably less than that planted to other crops like corn, rice and soybeans, of course with different social functions.

diverts 55% of the sugarcane to ethanol production and the remaining 45% to sugar production.[7]

In parallel to the expansion of sugar cane production and its traditional processed products (sugar and alcohol)[8], PROALCOOL earmarked part of its loans taken from the World Bank, to R&D activities. The latter included research on alternative raw materials for alcohol production (such as starch from cassava) but concentrated on the strengthening of sugar cane breeding programs[9] and on the improvement of new sugar extraction and fermentation processes as well as in the introduction of computer-assisted equipment for all industrial processes and utilization of sugar cane processing by-products.[10]

The knowledge generated by such R&D activities as well as the learning accumulated by the sugar cane mills resulted in considerable increase not only in sugar cane productivity but also in sugar and alcohol yields, as illustrated in figure 5. Another significant impact was a drastic reduction of production costs, not only of ethanol but also of sugar cane and sugar. Today Brazil is the lowest cost producing country of both ethanol and sugar. For the latter, figure 6 presents relevant comparative information with other sugar producing countries.

[7] In great numbers we can say that 1 ha of land produces an average of 82 ton of sugar cane that processed can yield either 7,000 litres of ethanol or 12 t of sugar with some residual ethanol from the generated molasses.

[8] A vast array of other 'secondary' products to be obtained from the sugar cane industry residues are either being researched or already being produced namely: sweeteners (glucose and xylitol), single-cell proteins, lactic acid, microbial enzymes, etc…

[9] In the 70's and 80's, Brazil had three sugar cane breeding programmes – one maintained by the Agronomic Institute of Campinas (IAC) and funded by the state of São Paulo; one funded by the sugar and alcohol producers who were associates of the Copersucar; and one funded by the federal government and carried out by Planalsucar (the research branch of the national Institute of Sugar and Alcohol). The latter alone had a research budget which was close to 70% of the one for EMBRAPA (the Brazilian Corporation for Agricultural Research, a state-owned R&D nationwide network of agriculture research centres and experiment stations). The point here is that in the 80's EMBRAPA comprised 37 research programmes for many different crops and livestock, whereas Planalsucar was totally dedicated to research on sugar cane and its products.

[10] At the beginning of the PROALCOOL program, stillage was discharged directly into riverbeds and caused very serious environmental problems owing to its biologic oxygen demand. However, the high content of nutrients and water in stillage makes it potentially useful for fertilization and irrigation of the soil. This has been a very important solution for some of the dry regions of Brazil. The use of stillage as a fertilizer increased sugarcane productivity, because the physical structure of the soil (mainly porosity) improved the water absorption capacity. As a consequence, agrotoxics and mineral supplements were saved.

Figure 5 - Evolution of yield of sugarcane (t/ha), ethanol (m3/ton of sugarcane), sugar (ton sugar/ton of cane) and content of total recoverable sugar (Ferreira 2002)

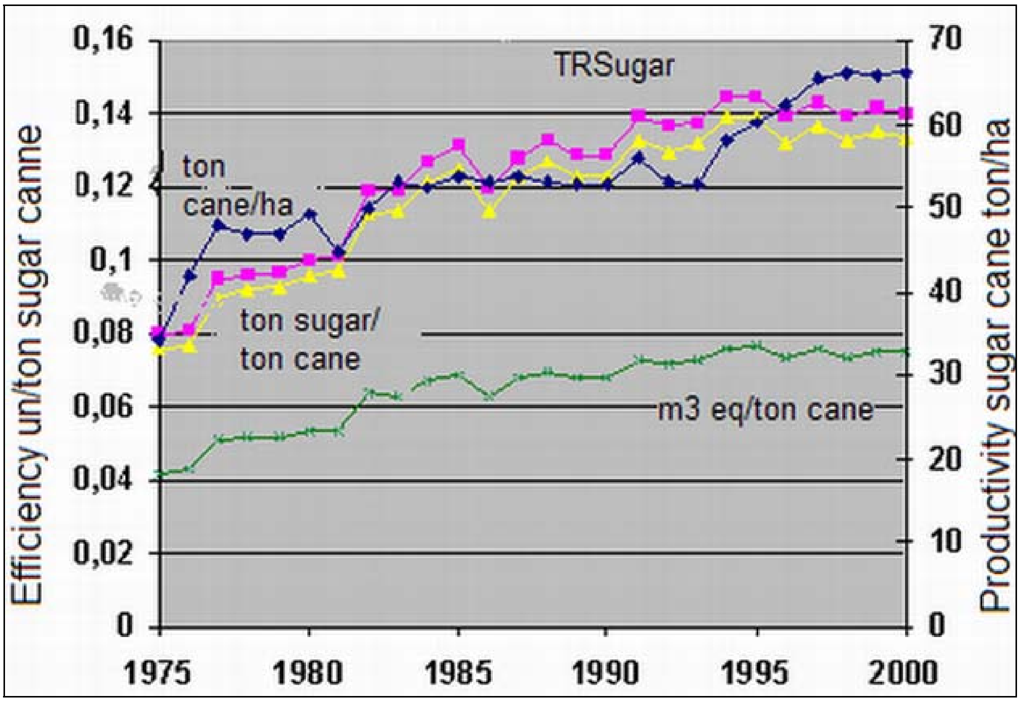
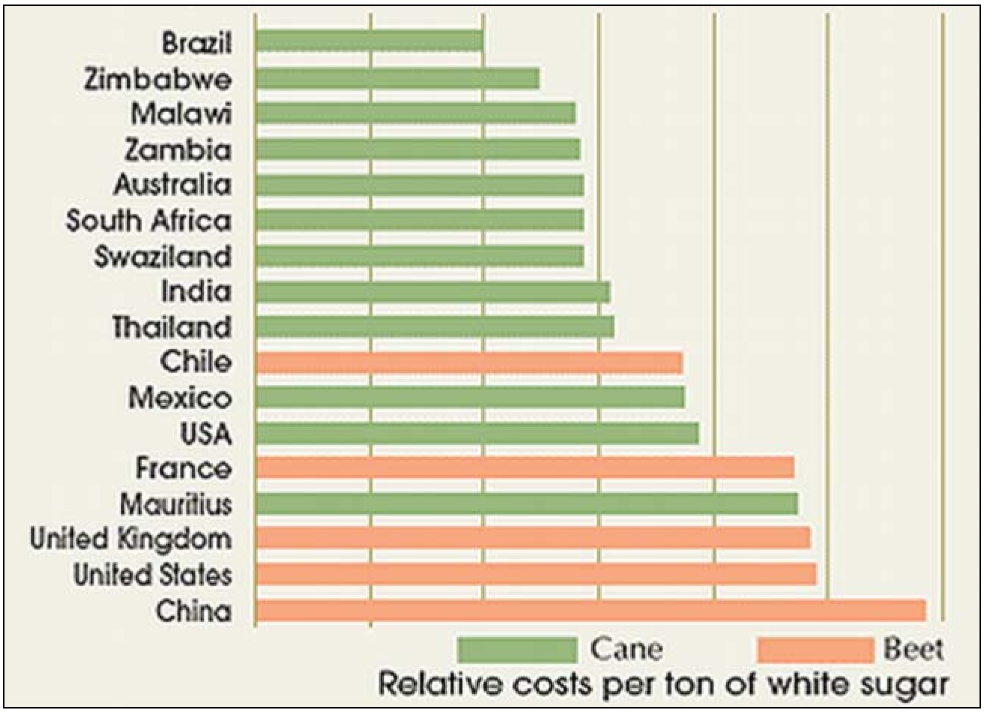


Figure 6 - Lowest cost sugar producers 2003/2004



Source: www.illovo.co.za/worldofsugar/internationalSugarStats.htm
(last accessed on 27/10/2005)

The combined government measures under PROALCOOL led the automotive sector in the country to divert its production to alcohol-powered vehicles. In 1980 the proportion of alcohol-powered vehicles was 30% of the total production, reaching 88% in 1983 and a remarkable 96% in 1986. This is a clear indicator that Brazil developed important technology for ethanol production and created a renewable source of fuel, produced independent of the world petroleum market.

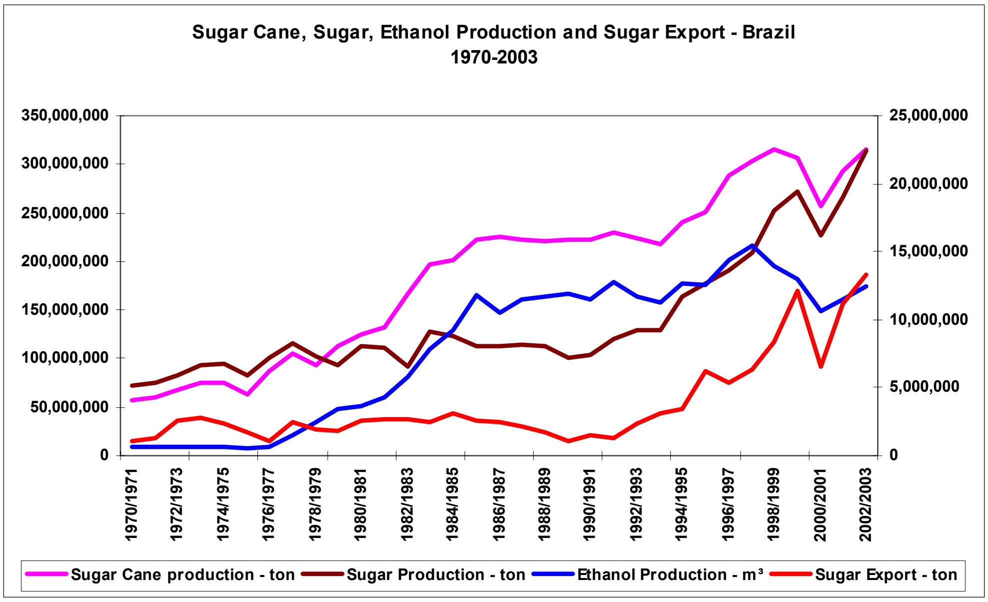
In the mid-80s, however real prices of oil in the international market started to show a deep decline – from over 60 US$/barrel in 1981, it dropped to less than 20 US$/barrel in 1986 (WTRG Economics, 2005[11]). In addition, Petrobras managed not only to find new oil reserves in Brazilian territory but also developed technological capabilities to exploit it both in land and off shore, considerably enhancing Brazilian production of oil. This forced the Brazilian government to reconsider its goals for the incentives to PROALCOOL. From the production side, the rates of establishment of new distilleries came to a halt from the late 80's as government loans at low interests were removed. Existing distilleries were also affected: at least 87 units were totally inactive in the harvesting year 87/88 (BNDES 1995). From the demand side, incentives for purchasing alcohol-powered vehicles, such as lower taxes both for buying and licensing the car and even the ethanol price at the filling stations began to vanish. This new picture, added to technical problems that still remained unsolved in relation to ethanol-powered vehicles led to a set-back of PROALCOOL. In 1990, the number of ethanol-powered vehicles produced dropped to less than 100.000 units, compared to over 700.000 in 1986. Such major policy changes took some years to

[11] www.wtrg.com, last accessed 15/10/2005

have a full impact, and peaked in 1998: the monopoly enjoyed by Petrobras was removed; ethanol prices were liberalized; subsidies paid to hydrous-alcohol producers were reduced from 0.98 reais per liter to 0.45 reais per liter; and subsidies paid to anhydrous-alcohol producers were totally eliminated (USDA, 2001).

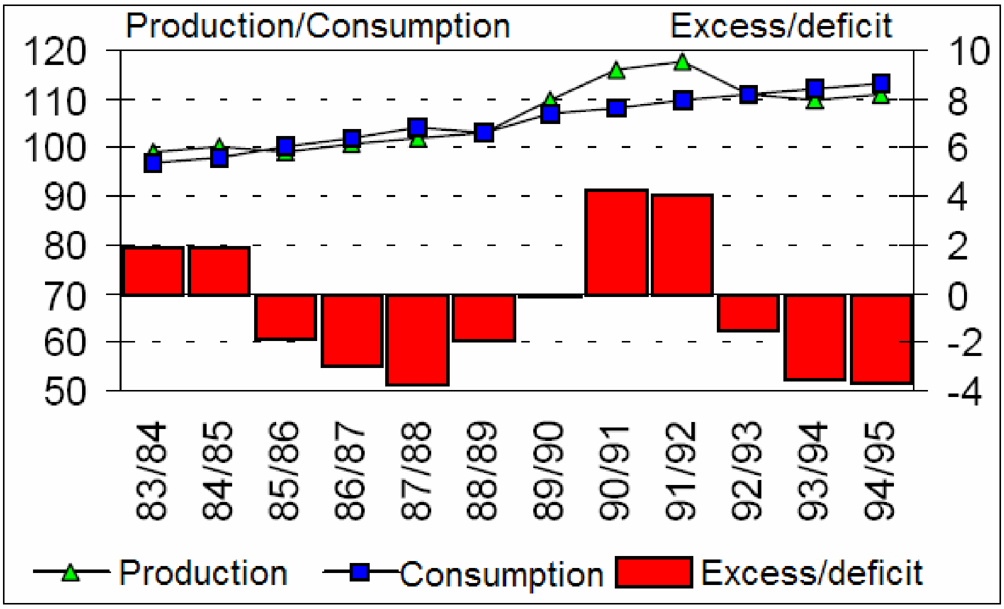
The decline in the ethanol demand was joined by a decrease of both international demand and prices for sugar, which started in the mid-80s, as shown in figure 7. The international scene became even worse for sugar in the early 90s when the world production exceeded consumption and led to a steep decline in prices (see figure 8). The consequence was that sugar and alcohol production park, whose capacity had been enhanced in the preceding years, was now partly idle. At the same time, research institutions which had enjoyed considerable financial support during the PROALCOOL and had specialized in the sugar and alcohol production chain were finding it difficult to obtain research funds from other sources and to re-direct their research efforts to other areas.[12]

Figure 7 - Sugar cane, sugar, ethanol production and sugar export in Brazil: 1970-2003



[12] In this period there was a complete restructuring of the sugar cane research system in Brazil. Some traditional government research institutes in the field, such as PLANALSUCAR were closed down. At the same time, sugar cane breeding programs carried out both by Planalsucar and Copersucar were discontinued.

Figure 8 - World production and consumption of sugar: 1983-1995



Source: Landell Mills Commodities Studies (1999)

This was the context in which the idea of producing a biopolymer from sugar was first discussed. Copersucar, a cooperative of sugar and alcohol producers in the state of São Paulo, was pushed by its associates to "search alternative products for the sugar cane production chain, adding value to the products, diversifying the portfolio, in order to make better and more lucrative use of the sugar cane processing industrial park" (CR). For helping them in this task, Copersucar looked for partners in the research system and started discussions with the Institute for Technological Research (IPT). What came out of such discussions that led to the development of a new process to obtain a bioplastic from sugar is what this article is about. In the following section the story begins to be told, with a focus on the social actors involved and their role.

3 Origins and development of the project for obtaining sugar-based plastic: the actors, their profiles and their role

The production process of cane sugar-based plastic in Brazil can be described in two quite distinct phases. The first initiated in 1991 with the approval of a research grant of about 2 million USD to a consortium of institutions, namely the Institute of Technological Research (henceforth IPT), the Institute of Biomedical Sciences of the University of São Paulo (henceforth ICB/USP) and the Technology Center Copersucar (henceforth CTC), each described below. The opportunity for the project appeared as at that moment the Ministry of Science and Technology was implementing the second version of a special S&T funding program called Science and Technology Reform Support Program (PADCT), whose funds came partly from a World Bank loan[13].

PADCT deals with both the university-based research system and the technology-using private sector, and includes several subcomponents which support very specific objectives (matching grants to SMEs, university/industry cooperation, promotion of intellectual property rights enforcement, etc.). PADCT also concentrates its research grants in a set of priority scientific disciplines and technological areas. Biotechnology was one of them and the sugar-based plastic project was then submitted to the Biotechnology sub-program (SBIO) of PADCT II, under a subcomponent called Research, Development and Engineering (PDE) which was managed by FINEP (a government funding agency linked to the Ministry of Science and Technology). PDE aimed specifically at larger projects, involving different agents (universities, government institutes and private firms) and providing support for all necessary steps leading to a potential innovation in product or process – from basic research to technology transfer to the productive sector.

The sugar-based plastic project submitted to and funded by SBIO/PDE/PADCT II through FINEP was entitled "Production of Biodegradable Plastics (polyhydroxyalcanoates) from Sugar Cane via Biotechnological Route" and had the goal to develop a new process for obtaining biodegradable plastic (PHB and its copolymer polyhydroxybutyrate/valerate [PHB-HV]) using sugar cane biomass and its products (mainly sugar) as substrate[14]. The project aimed at the development of the whole process - from the production of efficient microorganisms, fermentation and extraction phases to the transfer of the technology to the productive sector. To achieve this, a division of labor was negotiated and agreed upon between the three institutions involved in the project, namely, IPT, ICB/USP and CTC. Immediately after an agreement was reached between the three partners and as the technological trajectory to be explored was determined (choice of microorganism[15], fermentation, separation, extraction), a patent application was submitted to INPI[16] and was granted (number PI9103116-8[17]) in July 16, 1991. The patent at this point, therefore, protected the conception of a process to obtain PHB from sugar and not yet an existing technology. Granted the patent, the research work started with the disbursement of the first parcel of the grant in 1992.

It is important to mention that one important reason why such institutions got together in this project is because of previous knowledge of each other's work through PROALCOOL. As said in the introduction, PROALCOOL earmarked a fraction of its funds to R&D and the three institutions present here had already

[13] With negotiations starting in the mid- 80´s, the Brazilian government has succeeded in signing three agreements with the World Bank resulting in loans to fund strengthening and reform of the S&T system. PADCT I (started in 1985), PADCT II (started in 1991) and PADCT III (started in 1998) altogether amount to about 772 million USD, of which 377 million were provided by BIRD/WB loans. These programs had similar objectives but the idea of involvement of the productive sector in S&T activities played an increasing role from the first to the third program. There is not much documentation available in English about the PADCT, but basic information (both factual and analytical) can be found in www.mct.gov.br

[14] Public call for proposals SBIO 01/90-02

[15] IPT and ICB/USP work with three microorganisms: Ralstonia eutropha, Alcaligenes eutrophus and Burkholderia sacchari, http://www.plastico.com.br/revista/pm355/biodegradavel4.htm, pg.3. Ralstonia eutrophus is the bacterium that was genetically modified by ICB/USP and is used by PHB Industrial.

[16] National Institute of Intellectual Property, www.inpi.gov.br

[17] Patent holders are CTC and IPT. The latter entered into agreement with ICB/USP whereby they would equally share IPT's patent rights.

carried out research with PROALCOOL grants, and had either collaborated then or met each other in project workshops and conferences.

Concerning who had the central idea of the project and the initiative to bring the actors together to jointly write and submit a project to PADCT, it is not very clear. Apparently it was CTC who decided to invite IPT for the joint journey and IPT, then, invited ICB/USP as the need for more efficient fermentation organisms was clear. It seems that there was a convergence of interests of both IPT and CTC. The latter, as already said, needed to find alternative uses for sugar cane biomass as well as for sugar (given the decline of PROALCOOL and of the sugar prices in the international market), and IPT needed a new externally-funded project able to sustain the R&D capabilities and personnel it had built under PROALCOOL, and also needed to upgrade its laboratories. A short description of these institutions as well as the role they played in the sugar-based plastic project now seems to be appropriate.

3.1 The Institute of Technological Research (IPT)

IPT is a public research institute attached to the Secretariat of Science, Technology and Economic Development of the State of São Paulo. It was established over 100 years ago with the mission to "meet the S&T demands of the various industrial and engineering sectors and provide technological support to the productive sector"[18]. IPT is organized in multidisciplinary research units called "groupings" (agrupamentos), which are dedicated to develop processes and products in various engineering fields, with special focus on biotechnology, industrial recycling, new materials, petroleum, sanitation, and informatics[19]. Four of such research groupings were involved in the development of sugar-based plastic, namely: biotechnology, organic products, chemical processes and economic assessment.

The biotechnology grouping of IPT appeared in the early 1970s and had two main research lines: production of biogas from domestic waste and from sewage; and alcoholic fermentation, in an attempt to improve traditional processes in operation. They had, then, substantial funding from the Secretariat of Science and Technology of the State of São Paulo and also from PROALCOOL, which started to decline in the mid-80s. However, during almost 15 years of intense research activities, IPT gathered a considerable knowledge base and a critical mass of researchers – about 30 people - doing work on applied and industrial biotechnology. As the grouping was active in alcoholic fermentation it was almost "natural" to collaborate with CTC (the R&D division of the Cooperative of Sugar and Alcohol Producers, as explained below). And this they did during the PROALCOOL and even afterwards, although in much smaller scale.

The participation of IPT in the sugar-based plastic project apparently began when CTC approached the former with the challenge to search for alternative uses for sugar cane biomass and products, as the production chain leading only to sugar and alcohol was thought to be too limited. IPT and CTC spent about a year (1989/1990) searching, discussing and studying alternatives. One that stood out was the production of a biodegradable polymer from Carbon source which, in Europe, where the process had been developed, was thought to be sugar from beets or starch from potato or wheat. In the 1980´s ICI had built and started to operate a plant in the UK to produce this plastic but the price was too high at the time (about 30 USD/kg). It called the

[18] Detailed information on the technical and administrative structure of IPT is availabe at http://www.ipt.br/institucional/organizacao/estrutura/

[19] http://www.ipt.br/institucional/

attention of IPT and CTC, when searching the scientific and patent literatures, that energy was the main culprit for the high prices and that it would be possible to develop a process for the production of a biodegradable polymer from sugar cane biomass since the energy needed would be provided by the bagasse.

In short, according to the interviewees, IPT and CTC decided to bet in the alternative to produce bioplastic from sugar cane biomass, in detriment of other alternatives then considered, for a number of reasons. First, the literature showed the polymer to have interesting characteristics both in terms of its physical properties and biodegradability and also potential industrial applications. Besides, the ecological discourse was quite prominent in the national and international political agenda and they thought they could join it. More importantly, though, they firmly believed they could solve the production bottleneck met by ICI because:

> "the basic raw material we had in mind was sugar (sucrose) and we had it abundantly and at a very low production cost (differently from ICI); and the whole production process was designed to be installed inside a sugar and alcohol production plant so that all raw materials (from fermentation substrate to solvent and energy source) needed for the production of the polymer would be available inside the plant". (PR-Interview)

Thus, this was the main idea developed by the project submitted to PADCT in 1991, after a year of discussion, search, literature review, tasks allocation to different parties, and writing up. IPT took the leadership in project preparation and one of its senior researchers was chosen as the principal investigator, being the technical coordinator to respond for the project.

In the implementation of the project, IPT carried out the following tasks: developed the fermentation process and studied the fermentation parameters (kinetics of growth and production, operational conditions, control and scaling up to 100:1); developed the technology for extraction and purification of the plastic in laboratory scale; built the first casts and proofs with plastic material produced in bench scale to assess the potential utilization; conducted the first biodegradability tests and field trials according to international norms. The bench production unit built at IPT had the fermentation capacity of about 10 liters of sugar syrup and was able to produce 100g of PHB (CR). While developing parameters at this capacity level, IPT had a close interaction with CTC so that the transfer of technology from the former to the latter was constant.

Another important role played by ITP was to identify and invite another partner for the project, namely, ICB/USP, which had a fundamental part in the development of the process as will be described next.

3.2 The Institute of Biomedical Sciences of the University of São Paulo (ICB/USP)

The ICB/USP is represented in the sugar-based plastic project by the Laboratory of Genetics of Microorganisms and Biotechnology. This research group is a pioneer in the field of genetic engineering of yeast in Brazil and has obtained, over the years, many transgenic strains of yeasts with different applications. It is also important mentioning that the University of São Paulo is a public, state supported, university, the most prestigious one in the country and responsible for a considerable part of the mainstream scientific publications produced here.

Researchers from this laboratory were particularly active during the first phase of PROALCOOL during the 70s and early 80s. At that time, they carried out research projects aimed at obtaining strains of Saccharomices cerevisiae able to efficiently produce ethanol from starch, so as to include cassava as a complementary raw material to sugar cane. Given the accumulated knowledge of this group with the production of engineered yeasts as well as their familiarity with the sugar cane production chain, they were easily identified by IPT as important partners and invited to join the consortium.

ICB/USP concentrated on the improvement of the bacterial strains for fermentation. It was well known by them that polymers of the type PHA (polyhydroxyalconoates) are synthesized by a wide range of bacterial strains for the intracellular storage of Carbon and energy under adverse growth conditions and in the presence of excess Carbon sources. Ralstonia eutropha (or Alcaligenes eutrophus) is one of the most studied microorganisms for the production of PHA due to the ease of culturing this bacterium using renewable sources of Carbon and also because this bacterium can attain up to 80% of its dry mass as polymer (Marangoni et all., 2000). This bacterium, however, as naturally occurring, "was not able to produce the polymer using sucrose as substrate", and from the beginning the idea of the project was to use sugar as the raw material – "an abundant and low cost material" (AC). Therefore, the task of ICB/USP was to engineer a bacterium adapted to conditions defined by the project. And so they were able to transfer 5 gene sequences from another bacterium to Ralstonia eutropha and obtained a strain, which was patented, and is still the organism used in the existing production plant.

In the process of selecting and breeding the microorganism, different bacterium strains were screened and various other promising strains were identified that are efficient in producing polymers from sugar cane biomass. One of such, a bacterium isolated from soil of sugarcane plantation with a high yield of PHA was described in 1996 by one of the researchers working at IPT and was deposited at CABRI[20] with the name of Burkholderia sacchari. The innovative characteristic of this bacterium is that it is able to use bagasse as substrate, thus enlarging the possibilities of using different parts of sugar cane biomass as raw material for bioplastic production. A mutant strain of this bacteria as well as the process for obtaining it, with a higher capacity for producing copolymers from sugarcane, was patented in Brazil in 1998. All patents granted in the framework of the project, no matter who deposited it, belong to the consortium of the three institutions – IPT, ICB/USP and CTC. It is to the latter that we now turn our attention.

3.3 The Technology Center of the Cooperative of Sugar and Alcohol Producers of the State of São Paulo – COPERSUCAR (CTC)

Copersucar is a cooperative of 91 members, responsible for the commercialization of over 2.2 million ton of Brazilian sugar in the international market. This makes Copersucar the world's largest exporter of sugar.

In 1970, Copersucar created the Technology Center Copersucar (CTC) dedicated to R&D to attend the technical demands, solve the technical problems and anticipate the innovation needs of its associates. Since its creation, CTC contributed significantly to technological innovation, both major (such as the use of stillage as fertilizer) and incremental, in the entire sugar cane chain. The most visible of such innovations is the creation of new sugar cane varieties, the SP varieties, which are today cultivated in 50% of the area covered with sugar cane crop in the country.

[20] Common Access to Biological Resources and Information

In 2004, CTC was transformed in the Sugar Cane Technology Centre. The acronym CTC was maintained and so was the mission to develop technological contributions to the sector. CTC is no longer an exclusive R&D arm of Copersucar associates, but is open to all interested sugar cane, sugar and alcohol producers, who are willing to become members. The latter today include over 100 sugar mills and cooperatives of sugar cane growers. CTC is financially maintained by contribution of its associates who are granted privileges over the use of R&D results and get technical assistance at reduced prices[21].

The role of CTC in the sugar-based project was crucial of course. CTC developed the technology for extraction and purification of the plastic via solvents. This task was accomplished together with IPT generating the patent PI 9302312-0. The latter also had an important participation in optimizing the fermentation process by investigating and testing the dimension and number of reactors. The main task of CTC, however, was to scale up the laboratory bench process set up at IPT with the latter's assistance. This involved the transfer and adaptation to a pilot unit of intermediate scale (10kg of PHB/batch of fermentation of about 150 liters of sugar syrup) which they had to build and operate at CTC headquarters. In the course of doing so, a number of engineering problems appeared, especially those related to the extraction of the polymer, which were solved jointly by CTC and IPT technical personnel. It was on the basis of the engineering information provided by this pilot unit that it was possible to elaborate a pre-commercial industrial project for the production of 5 ton of PBH/year.

In 1994, the technological process for obtaining the biopolymer PHB, at a bench unit of intermediate scale, was considered to be ready. In addition, CTC had developed a pre-commercial industrial project for PHB production of a pilot production unit that could reach 50 to 60 ton PHB/year when at its fullest capacity, but would start off with not more than 5 ton of plastic/year. At this point Copersucar called its members for a demonstration meeting. The latter aimed at finding partners among Copersucar associated sugar mills where to install the pilot production unit. The idea of this pilot plant was to produce enough PHB to supply the market for tests and trials. Also, this pilot plant was intended as a training facility for the future operators and to provide data both for scale-up and economic evaluation of the process.

Usina da Pedra (henceforth UPedra), a traditional sugar and alcohol producing industry, volunteered to run the risk and went into agreement with Copersucar. The contract established that UPedra would incur the costs of building, buying the necessary equipment and operating the pilot plant and would keep a detailed record of expenditures. If the project were successful, Copersucar would then reimburse the costs giving priority to UPedra to license and use the technology. In case of failure, UPedra would account for the financial losses. The formal contract also had IPT and ICB/USP as signatories as it included payment of royalties for the use of the process patent that is collective held by the three institutions.[22] The time frame of the contract was 5 years from June 1996 (giving UPedra a year to build the unit and start operation), after what IPT was free to look for other partners willing to explore the technology in case UPedra did not commercially produce PBH in 2001.

In 1995, the pilot production unit started operation with technical assistance from CTC and occasional visits from IPT. In 1997 the production capacity reached 8-10 ton PHB/year, that is, 20% of the full capacity of pilot project design. On the one

[21] *http://www.ctc.com.br/php/pagina.php?doc=oque_somos*

[22] The contract says that 3% of the plant revenue is to be paid for used of the technology: 1.5% goes to Copersucar and 1.5% is to be equally shared by IPT and ICB.

hand, there was no point in producing more than needed for tests and trials, on the other, yields were very low due to technical adjustment problems. Despite this, the pilot production unit provided relevant data for an economic assessment of the process. The latter revealed that "the production cost of PHB using the process developed by IPT and CTC and scaled up at UPedra was between 2 and 3 USD/kg. This was extremely favorable when compared to costs estimated by ICI in the 80's (between 20 and 30 USD/kg) and later by Monsanto. The latter bought the plant from ICI, and was able to decrease costs to 14 USD/kg but decided eventually to close it down in the UK" (PR)[23]. This cost estimate was based on two scenarios: an autonomous unit producing 10,000 tons of PHB per year, located outside the mill site, and an integrated unit having the same production capacity. There were clear cost advantages of integrating PHB production with an existing mill, but even for an autonomous PBH plant costs did not go over 3 USD/kg (Rossel et all., 2005).

From 1997 to 2000, the process was considerably improved and partnerships were established between CTC and plastic processors and transformers to search commercial applications for PHB. In 2000, UPedra concluded that the pilot project was successful and wanted to completely get hold of it, license the technology and go commercial. This is when a second phase of the sugar-based plastic process begins. A description of how UPedra proceeded in order to achieve its objectives will now follow.

3.4 Usina da Pedra and PHB Industrial S.A. (PHBISA)

> "To be recognized globally as the first company in the world to produce PHB, from a renewable source, in a commercial scale with clean technology and ecologically correct." (the vision of PHB Industrial) (www.biocycle.com.br/sit.htm)

In the year 2000 the firm PHB Industrial SA was created, the pilot production plant was remodeled, the process adjusted and started operating at the fullest capacity of 50-60 ton PHB/year and its product received the name of Biocycle.[24] From this point onwards, operation control and decision making passes exclusively to PHBISA. Copersucar, as agreed by contract in 1995, has to reimburse the costs incurred by UPedra in the installation of the pilot production unit. Copersucar pays its debt by granting UPedra the right of use, at no cost, to all equipment that belonged to Copersucar and was operating in the pilot plant.

PHBISA is an equitable partnership between two strong and traditional groups in the sugar and alcohol industry – Biagi Brothers (owners of 5 plants, including UPedra) and Balbo Brothers (owners of 3 sugar and alcohol mills). The spoken person for PHBISA maintains that UPedra was from the beginning involved in the search for new alternative uses for sugar cane biomass and they were the ones that prompted Copersucar to embark in the prospecting (SO). This, to a certain extent, explains the readiness of this company to respond to the call for partners from Copersucar in the demonstration meeting mentioned above. The rationale for the decision to embrace the initiative was explained by one of the interviewees:

[23] Biopol, a PBH copolymer compounded resin produced by Monsanto was sold at a price of USD10,00 to 20,00 per kg, depending on grade (Nonato et al, 2001, p.4).

[24] Deposited at the INPI under the number 823034437 in 21/02/2001.

> "Sugar and sugarcane are our business. Biopolymers from sugar represent a business with a future, made with a clean technology, linked to environmental preservation, able to be integrated to the production process already existent in our mills and would make possible to use part of the equipment that traditionally, given the production cycle of sugar cane, is idle at least half of the year". (SO pp.10)

Implicit in this quote is the idea that one important benefit of associating PHB production to sugar mills is the fact that the latter are quite efficient in sugar production and have a long history of accumulated knowledge and competencies in the entire chain from producing sugar cane plantlets free of diseases to high quality sugar.

After the conclusion of an economically viable production process, in 2004, a commercial plant was projected with a capacity of 2,000 ton/year (Pessoa Jr. et al, 2005). The plans are for continuous expansion to 5,000, then to 7,000 and then duplicating to 14,000 ton PHB/year. At this moment it is still regularly operating on a 60 ton/year basis, exporting about 80% of its production, while using the remaining product as samples for developing applications. Production costs are said to be barely covered by sales, as the economic viability of the enterprise requires a 10,000 ton/year plant.

This break-even point has been known at least from 1997. The construction of a 10,000 tons-per-year PHB production unit demands a large investment. Installed equipment for the fermentation plant is estimated in US$ 15,000,000, the extraction and purification unit accounts for another US$ 15,000,000 and utilities for US$ 5,000,000. Land, civil works and buildings are estimated in US$1,000,000 for the fermentation plant, US$ 1,600,000 for the PHB recovering facilities and US$600,000 for the utilities unit. This adds up to a total investment of about US$38,200,000.00 which, allegedly, is equivalent to building a new sugar mill with the capacity of UPedra. PHBISA argues it needs commercial partners to be able to cope with the necessary investment for upgrading to this scale (SO).

The route to develop a viable process in today's scale of 60 ton/year has not been always smooth, in the perception of the protagonists. It required considerable investment both in terms of capital and training of human resources and a long process of learning about the technology. Even more difficult was and has been the search for users of the PHB, so as to establish commercial partners in the longer run. Here seems to lay the crux of the matter: to developed applications for PHB and to create a market for them.

In view of this, it comes as no surprise that PHBISA has been extremely active in putting together a vast array of researchers from different fields, at the national and international level, as well as industrial processors and transformers of polymers, in addition to consultants from diverse areas in order to develop commercial uses of and promote the PHB. Various areas of application have been experimented with and there is rumor that big chemical corporations like BASF have received large quantities of PHB for testing[25]. According to PHBISA spoken person, the following areas of application are under investigation (Ortega Filho, 2003):

- Injection technologies
- Extrusion Technologies/ Thermoformer

[25] BASF is said to have organised an internal seminar that brought together its own R&D personnel with PHBISA representatives to exchange information about PHB. This is taken as an indication of BASF's interest in the product, as the word goes "because PHB blended with biodegradable plastic derived from oil adds desirable features to the latter".

- Cosmetic packaging
- Food packaging
- Packaging for Pesticide
- Agriculture (cups for seedlings)
- Medical area (prostheses, controlled release for medicine, suture, etc)

An informal research network has been established, members of which receive under request, samples of PHB to develop tests for different applications, biodegradability, development of blends and use in different products. This is very important because none of the parties involved in the project up to 2000 had any experience with the production or application of either the PHB or any other kind of polymer. From 1995 till 2000, UPedra operated the unity in order to test the viability of the process, to train the personnel on the job, to fine tune the operational system of the factory and to have samples of the product distributed to concerned researchers and developers. In 2000, with the creation of PHBISA, it was clear that for commercial operation the firm had to develop new skills in product development, commercialization and after-sales assistance. This pointed to materials engineers specialized in resins that could perform trials for the characterization of the product and develop blends for new uses. Such expertise, they found out, was available at the Department of Materials of the Federal University of São Carlos.

3.5 Department of Materials of the Federal University of São Carlos (DEMa/UFSCar)

In 2000 DEMa/UFSCar was invited by PHBISA to become the reference center for product trials and research on applications of PHB. Although the researchers working at that department had never worked with biodegradable resins before, they were very active in traditional polymers and had a high scientific reputation in the field.

The agreement between the two organizations was that PHBISA would send samples of all fermentation batches to be analyzed by DEMa/UFSCar so that a consistent characterization of the product would be achieved. In the last five years, over 250 samples were analyzed and the result is that "the product today has a technical specification... with slight variations given the complexity of the process... It is possible to say that the product has a technical label and commercial features. In short, it is a consistent product" (Interview -JA).

Nowadays, DEMa/UFSCAR is building a 300 m² new lab to be called the Centre for Biodegradable Polymers, to work as a reference center for analysis of biopolymers. The lab will be dedicated to trials for product characterization and biodegradability as well as to research on polymeric blends with PHB. The construction of the lab, all equipment and apparatus are covered by PHBISA, who has also hired a full time senior researcher and technicians.

It is important to stress that in the course of the development of Biocycle, from its initial phase in 1990, a network of interested parties was established, became more complex and intensified during the last years. At the beginning, the network was formally constituted by three institutions (IPT, ICB/USA and CTC); in 1995 incorporated one sugar and alcohol producing group (Biagi of UPedra); was officially transformed in a joint-venture in the form of the PHBISA in 2000 (in partnership with another producer, Balbo Brothers); starting to contract works of the DEMa/UFSCAR in the same year. This notwithstanding, a much more complex network of actors has been formed around the project, now an enterprise, constituted by researchers of other universities, industrial polymer transformers, consultants; users of polymers.

It was not possible to identify all institutions and organizations that have asked for samples of PHB for research or for developing applications. The fragmented information indicates that this network is active in exchanging experiences and knowledge about the new process and product. The academic sector is the most visible component of this network and, since academics publish, it is possible to detect the dynamism of the network by tracking scientific publications. A complete list of publications directly linked with the development of Biocycle from the original research project in 1991 to the brand name of today is presented in Annex 1.

In this section we presented the history of the development of a process to obtain biodegradable plastic (PHB) from sugar, focusing on the actors involved and their role. A summary of the main events in chronological order is presented in the box below.

Chronology of the development of PHB

Phase 1: IPT, ICB/USP and CTC. Later on, Usina da Pedra

1989 – CTC approaches IPT to search alternative uses for sugar cane biomass and products
Biodegradable plastic (PBH) is chosen as the route
1990 - IPT elaborates the research proposal "Production of Biodegradable Plastics (polyhydroxyalcanoates) from Sugar Cane via Biotechnological Route" for submission to PADCT (Science and Technology Reform Support Program partly funded with a World Bank loan)
1991 – Project approved by PADCT.
A patent application for the conception of a process to obtain PHB from sugar was submitted to INPI and was granted (number PI9103116-8)
1992 – COPERSUCAR enters into a consortium with IPT (and ICB/USP) to develop the technology for PHB production.
Disbursement of the first parcel of PADCT grant and work begins
IPT develops a bench production unit: fermentation capacity of 10 liters of sugar syrup and production of 100g of PHB
1993 – Copersucar decided to build a pilot unit at its headquarters in the light of the results obtained by IPT – unit capacity: 10kg of PHB/batch of fermentation of about 150 liters of sugar syrup
1994 – Copersucar pilot unit adjusts engineering parameters and is considered a success.
CTC develops a pre-commercial industrial project (pilot production unit)
Demonstration of the CTC pilot unit of the project of a pilot production unit to Copersucar associates
Usina da Pedra volunteers to host the pilot production unit and starts its construction with technical support from CTC
1995 – Pilot production unit at Usina da Pedra starts to operate with technical support from CTC
1997 – Pilot production unit is operating at 20% of its capacity (8-10ton PHB/year).
Copersucar establishes partnerships with plastic processors in Brazil and abroad to search for commercial applications of PHB.

Phase 2: PHB Industrial SA

2000 – Joint Venture between Biagi e Balbo for creation of PHB Industrial SA and the trade name of Biocycle for the product
Plant remodeled to reach fullest capacity of 50-60 ton/year
Department of Materials of the Federal University of São Carlos (DEMa/UFSCar) becomes the reference center for product trials and research on applications of PHB
2004 – Conclusion of an economically viable production process
Project for commercial plant with a capacity of 2,000 ton/year to be expanded to 14,000 tons/year
2000 to 2005
– Technical specification of PHB by DEMa/UFSCar
Search for PHB applications and market creation
Links with polymer processors, transformers, users and academics

But exactly what is the rationale and nature of the process developed and what it consists of has not been described yet. This is what will be presented next.

4 The technological process for obtaining a sugar-based plastic (PHB) in Brazil

The development of new and biodegradable compounds in order to replace hazardous chemicals in industrial activities has been a privileged task for many countries in their R&D activities and among those chemical material, plastic polymers is indeed one of the main targets. One trend of research in this line is starch, and packing material is already at a considerable use in many countries although physical and chemical properties of starch polymers have so far prevented a wider application for other industrial purposes in substitution for plastic. New biotechnologies are under way and according to some scientists, those technologies are almost mature to give polyhydroxibutyrate research and production a boost that could happen through the development of transgenic plants like corn and others, with the ability to synthesize great amounts of the compound which could produce a cost-effective biodegradable polymer for the plastic industry. So far, the main deterrent in the development and adoption of biodegradable substances like plastic as a replacement for traditional and non-biodegradable hydrocarbon compounds is cost effectiveness.

Development of biodegradable plastics is not a new idea. Attempts to develop different kinds of starch based plastics are reported in the literature[26] and elsewhere with varying degrees of success. Table 4 gives some examples of the products obtained from different sources and their characteristics and costs. PHB/V, the focus of our discussion, is listed in the literature at a price of between 7 and 13 USD/kg. This is considerably more expensive than the production costs estimated for the process developed in this case study.

Table 4 - Price of biodegradable plastics obtained form different sources and routes

Price of some biodegradable plastics **Material**	**Cost, $/kg**
Cellophane	5
NC-W/ Cellophane	5
Cellulose Acetate	3-5
Starch/PVOH	3-7
PHB/V	**7-13**
PLA	2-11

NC-W = Nitrocellulose-wax *PVOH = Polyvinylalcohol*
PHB/V = Polyhydroxybutyrate/valerate *PLA = Polylactic acid*
www.ftns.wau.nl/agridata/historybiodegrplast.htm

[26] http://www.ftns.wau.nl/agridata/historybiodegrplast.htm

The biodegradability of plastics depends also on the chemical structure and constitution of the final product and not only on the raw materials used in the production process. Biodegradable plastics may be based either on synthetic or natural resins. Natural biodegradable plastics are obtained from renewable resources (particularly feedstock) such as starch or simple sugars like glucose, fructose and sucrose, the latter being the source of the process presented here. Conceptually, the term biodegradable plastic will be used here to refer to resins that are degraded by biological activity, particularly by enzyme action leading to significant changes in the materials chemical structure. In essence, biodegradable plastics should break down cleanly, in a defined time period, to simple molecules found in the environment such as carbon dioxide and water.[27]

Discussions on the viability of the development of biodegradable plastics have been intense in the last two decades. Despite the limitations on functionality (e.g. sensitivity of humidity for starch, brittleness for polyhydroxybuterate [PHB] and lack of flexibility in producing specialized plastic materials) the advantages of potential uses for specific ends is clearly recognized. The main uses of biodegradable polymer resins are for items for which disintegration after use is a direct benefit. Examples include agricultural mulch films, planting containers and protectors, hay twine, surgical stitching, medicine capsules, and composting bags.

Biodegradable polymer resins hold great promise to compete in the plastic materials and resins market. Between 1987 and 1992, the value of shipments for the overall industry grew from $26.2 billion to approximately $31.3 billion. Based on constant 1987 dollars, this translates into a 4.6070 annual increase.In 1992 biodegradable polymer resins captured less than 5 million pounds or roughly 0.08070 of the plastic materials and resins market (Uri et al, 1995). It is a consensus among experts and analysts that the reason that biodegradable polymer resins are not making greater inroads into this market currently is based on costs.

Technical limitations and high costs not withstanding, as the world enters a century with new priorities for renewable energy and management of waste, with tougher environmental legislation such as extra taxes on conventional non-biodegradable materials, there is renewed interest in biopolymers and the efficiency with which they can be produced. Therefore, an increase in the use of biodegradable polymer resins will require some sort of active government intervention in the market for plastic materials and resins.

Accordingly, as Nonato et al (2001) point out "the development of a biodegradable plastic commodity market may only be feasible if a drastic reduction of the production cost is achieved" (p.2). New technologies in processing are probably the most appropriate route to narrow the cost differential between synthetic plastics and bioplastics, as well as to improve material properties.

Despite being central, reduced costs is not the only condition to be met if biodegradable plastics are to be a commercially viable commodity. It is also most

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[27] The American Society of Testing and Materials (ASTM) defines 'biodegradable' as the matter "capable of undergoing decomposition into carbon dioxide, methane, water, inorganic compounds, or biomass in which the predominant mechanism is the enzymatic action of microorganisms, that can be measured by standardized tests, in a specified period of time reflecting available disposal condition" and the biodegradable plastic should break down cleanly, in a defined time period, to simple molecules found in the environment such as carbon dioxide and water.
http://www.deh.gov.au/settlements/publications/waste/degradables/biodegradable/chapter1.html , p.2

relevant that the whole life cycle of the bioplastic is environmentally sound. This is the assumption underlying the process of production of the PHB developed in the case described here. PHB refers to the Polyhydroxybutyrate (PHB) and its copolymers with polyhydroxyvalerate (PHV) that are melt-processable semi-crystalline thermoplastics made by biological fermentation from renewable carbohydrate feedstock – in this case, using sugar. PHB has been described as "the first example of a true thermoplastic from biotechnology" and is also biodegradable. Although quite stable under everyday conditions its degradation rate is very high at its normal melt processing[28].

The integration of the PBH production plant into a sugar mill in the Brazilian context offers unique advantages not only for cost savings but also for an environmentally sound process. First of all advantages is the availability of low price and large quantities of sugar. Brazil, as already mentioned, is not only the largest sugar producing country, but also the lowest cost sugar producing country in the world. Secondly, sugar mills have availability of energy -both thermal and electric- from low cost and renewable sources (bagasse); effective residues and waste disposal management both from the production process and purification and separation process; know-how and facilities for large-scale fermentation process; availability of biodegradable and natural solvents (by-products of ethanolic fermentation) produced inside the sugar mill and used to obtain PHB with a high degree of purity. (Nonato et al, 2001).

The production process of PHB developed in by this case is described by Nonato et al (2001, p. 3), who are literally quoted here:

"The process comprises a fermentation step, in which strains of Ralstonia eutropha […] are aerobically grown to a high cell density in a well-balanced medium consisting of cane sugar and inorganic nutrients. Cell growth is then shifted to PHB synthesis by limiting nutrients others than the carbon source, which is continually fed as a high-concentration sugar syrup. After 45-50 hours, the fed-batch fermentation process is stopped, with a final dry cell mass of 125-150 kg/m^3, containing nearly 65-70% PHB. The fermented medium is thermally inactivated in a heat exchanger, diluted with water, and flocculated. Separation and concentration procedures yield a cell sludge containing 20-30% solids which is then submitted to a multi-stage extraction process with medium-chain-length alcohols in continuous-stirred tank reactors.[29]The extract is purified for cell debris removal and then cooled down to recover a PHB gel. Solvent from the gel is removed by mechanical and thermal concentration. The resulting PHB paste is mixed with water and distilled to remove the remaining solvent. PHB granules are then collected by a sleeve, vacuum dried, compounded and extruded as pellets."

This procedure yields a highly pure polymer by solvent extraction, avoiding the negative environmental impacts of other processes. It is important to highlight once more that the production of PHB from sugarcane was conceived (by IPT and CTC) as a process to be integrated into sugar mill operations, using not only sugar as substrate but also all the facilities the mill can advantageously offer, such as heating and cooling, electrical power, water and effluent treatment and disposal. This is why production

[28] http://www.azom.com/details.asp?ArticleID=1881

[29] The latter is a considerable improvement over previously existing processes for PHB obtention that used chlorinated organic solvents that are usually hazardous to human health and the environment. In the process developed here, solvent extraction and purification of PhB is the Isoamylic alcohol, a by-product of ethanol fermentation which offers no risk to human health nor to the environment (Rossel at al, 2005).

costs have been estimated at such a low value when compared to other processes available in the literature.

The expectations for the development of industrial PHB production by the sugarcane agroindustry are high. According to some experts, there is a large margin for improvement in the current production process, which will result in lower capital and production costs, less generation of solid and liquid effluents and lower consumption of energy. Above all, there is the possibility of using sugar cane bagasse instead of sugar as substrate, which would further decrease production costs[30]. Actually this research line of obtaining a bacterium able of fermenting the pentose and hexose sugar contained in bagasse has also been pursued by IPT and ICB/USP, and a strain with this feature has been obtained and patented (Bramer et allii, 2001). Using this bacterium, however, would imply a number of changes in the process which are not in the agenda at this moment.

5 The financial dimension of the development of the process

Given the number of actors involved in the different phases and activities of process development, an estimate of investment from all parties is not an easy task. Financial resources involved in the First Phase of the process development were estimated by Copersucar and are shown in Table 5. This is probably underestimated because it does not show the amounts spent by UPedra in the establishment and operation of the pilot production plant from 1995 to 2000.

It should be noted that government support was also granted in the form of full scholarships to Master and PhD candidates working in the project. Despite its importance, there is no available information about the amount of money disbursed in the form of scholarships. We know, however, that 15 Masters and 3 PhD degrees were granted to candidates that did their research work in the framework of the project.

Concerning the Phase 2 of the process development, the investment made by PHBISA is treated as business secret. The only information they declare is a flat amount of US$ 9,000,000.00 up to now. In this phase there is also investment from government research agencies. This is the case of FAPESP (the Foundation for Research Support of the State of São Paulo) that granted the amount of US$ 135,000.00 to a research project of DEMa/UFSCar in partnership with PHBISA. Another grant to the same partners has recently been approved, but the amount has not yet been made public. Also, FAPESP as well the federal government agencies like CNPq and CAPES support Master and Doctoral candidates working in different aspects of PHB production and applications in different universities across the country.

[30] *The production cost of PHB is strongly dependent on the price of sugar, which is the major factor, accounting for almost 29% of the final cost.*

Table 5 - Estimated investment in PHB production process development

Organisation	Purpose	Amount (US$)
FINEP	To IPT and ICB/USP, lab equipment, purchasing materials and other research expenses	1.843.666,00
IPT	Own resources for personnel (up to 06/98)	901.778,72
Copersucar	Personnel involved in pilot unit at bench level and preliminary studies	167.124,00
Copersucar	Purchase of equipment and lab materials	44.307,00
Copersucar	Personnel allocated to the project, start-up and follow-up of the pilot production plant at UPedra	2.078.220,00
Copersucar (Usina da Pedra)	Purchase of equipment, materials, assembling, maintenance and operation of the pilot production plant at UPedra	2.476.724,00
Total		7.511.820,00

6 Outputs (academic and proprietary) of the project

Along with the R&D activities developed during the last decade by the different actors, a significant number of qualified professional expertises in the field of sugar-based plastic have been formed. Although, none of the institutions involved in the development of the process had explicitly committed itself to train academic human resources in the framework of the project, the fact that the project involved R&D activities, part of which was carried out by ICB/USP and IPT (both involved in graduate education) as well as by DEMa/UFSCar led naturally to this.

We looked into the databases of the three most important government agencies that grant scholarships for graduate education and found a number of candidates who did their research work on the topic, most of the times supervised by researchers directly involved in the project. This reveals dynamism in the acquisition and production of knowledge on biopolymers in Brazil. It is worth mentioning that before 1990 there were no publications on biopolymers in the country.

The most visible face of the knowledge generated and the human resources trained is revealed by the number of MS thesis, PhD dissertations and scientific publications linked to the project. This is summarized in Table 6.

Table 6 - Outputs of the Development of the Process of Sugar-based Plastic

Activity	Number
MSc Thesis	15
PhD Dissertations	3
Papers National Journals	31
Papers Internacional Journals	31
Patents & Registration	10

7 Summary of the key features of the development of the process

7.1 Absorptive capacity and firm learning

The objective of the project was to produce a bioplastic (PHB) from sugar in an environmentally safe way integrated to a Sugar Mill. This context, with its large quantities of readily available and comparatively low-cost sugar, as well as accessible thermal, mechanical and electrical energy obtained from renewable agricultural sources, was conceived to be the optimum place to introduce a large-scale facility for its production.

The concept of the project itself was innovative. The literature pointed to a series of limitations in the production process of PHB, such as: high costs due to energy requirements, use of toxic solvents, among others. The integrated production process to a sugar and alcohol mill was soon recognized as a clever solution to the limitations, to the point that the idea itself was patented. The process was developed in a successful way. It involved the generation of new basic knowledge (genetic engineering of bacterium strains for fermentation); development of the fermentation an extraction process; engineering and upgrading to pilot units of increasing capacities (from 100g of PHB /batch of 15 liters to 60ton/year). Although not a part of the original project, R&D is now being carried out for developing applications for PHB. In short, the process development was totally based on locally generated knowledge (except for the international literature) and involved all types of R&D activities (from basic research to learning by doing in operating a totally new plant).

This was possible for two main reasons, first of all, because capacity both in R&D and in manufacturing in related fields had already been developed. This exiting capacity included qualified research teams in universities and government institutes; accumulated knowledge in sugar cane, sugar and alcohol production, etc. For instance, the interviewees made clear that the main steps in the production of PHB are fermentation and extraction. Although fermentation for ethanol production is not the same as for PHB production, experience accumulated in the former was of significant use for the latter. The same is true concerning the extraction step of PHB and the processes of sugar crystallization and drying. Therefore, the process development built over existing expertise and skills, despite having to generate new knowledge. To this extent, as well as to the extent that the PHB production unit was within the borders of a sugar mill and managed by people familiar and experienced with sugar and alcohol production, it is reasonable to assume that PHBISA had significant absorptive capacity to assimilate the new process.

The second reason has to do with funding. The research project would not have been developed without the government PADCT grant. Copersucar and PHBISA (the private productive sector) only got involved and invested considerable amounts in R&D and in installing the pilot units because of the favorable results produced in the framework of the PADCT funded project.

7.2 Linkages and interactions

It is clear that process development was possible only because a dense network of institutions and people was formed. From its initial phase in 1990, a network formally constituted by three institutions (IPT, ICB/USA and CTC) established, became more complex and intensified during the last years. It is curious that the three institutions originally involved are a classic triad: academic researchers, government institutes and private sector. It even suggests a "linear" innovation process from basic research to process and product innovation (actually, to a new industry in the country). Now that the process seems to be under control by PHBISA the network formed aims at a different target: product application and market creation. This network is even more complex than the first one, involves academic researchers from various universities but also a large number of private companies – from plastic processors and transformers to users.

7.3 Industrial policy

The government scheme that made this project possible was, strictly speaking, designed as an S&T policy instrument. Although one of the pillars of PADCT was to foster interaction between the academic and the private sector, it is a long way to say that PADCT can be considered part of national industrial policy.

Having said that, if one thinks about the PROALCOOL and the impact it had on various public policies – from energy to transport policy, to agricultural, social (job creation, migration from the NE to the SE regions), environmental and industrial policy (related to the automotive industry, ethanol production, etc) – and if we can agree that the motivation for the PBH project was generated by the rise and fall of PROALCOOL, then it seems reasonable to establish a link between our case and industrial policy. For example, had not the ethanol market been liberalized and the subsidies for sugar and alcohol production eliminated, it is quite possible that the motivation for alternative uses of sugar cane biomass would not have been triggered. But this we can only guess…What can the said beyond any reasonable doubt is that the sugar-based biopolymer (the Biocycle) is a successful case of S&T policy aimed at promoting R&D and technology transfer to the productive sector.

8 Concluding remarks

The case analyzed here provides evidence that given the right conditions, resource-based industries can become knowledge intensive. It also shows that the knowledge and experience and skills accumulated in resource-based activities (sugar cultivation and refining) can be exploited in a different sector (plastics production), in this case, allowing the establishment of a totally new industry.

Success of the sort reported here, however, does not happen "naturally" or "inexorably". It requires pro-active attitudes from all actors, a negotiation of interests, commitment from all parties to the agreement, and government investment. In short, the following aspects should be highlighted as contributing to the success of the sugar-based plastic:

- the relevant actors had already experience of working together during the Proalcool (this points to the difficulties of evaluating impacts of R&D programmes)
- the previous investment of both government and the private sector (represented by Copersucar) on R&D in the sugar and alcohol agro-industry
- The existing research capacity in public sector research system (universities and public research institute)
- the existence of government research schemes to strengthen research capacity in biotechnology and foster linkages between the public and private sectors

Despite being considered successful, it must be remarked that a viable commercial plant of PHB is yet to be built. There are signs that this will happen in the near future, as the expected market for PHB comes true, but this is not yet the case. The future will tell.

9 Annex 1: Relevant scientific production produced in the framework of the development of sugar-based plastic in Brazil

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Entrevistas realizadas durante os mêses de agosto, setembro e outubro de 2005

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The manufacture of biodegradable plastics from maize starch: a case of technological migration, adaptation and learning in South Africa

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February 2006

Chapter 3: The manufacture of biodegradable plastics from maize starch: a case of technological migration, adaptation and learning in South Africa

Abstract

This paper explores the role of collaborative partnerships and linkages in the diversification process of firms, particularly those that have moved from primary resource-based activities into high-value niche applications. A two-year government funded project focused around the production of biodegradable plastics from maize starch in South Africa is used as a case study from which to "unpack" some of these issues. Although existing polymer processing equipment and imported high-grade maize starch were used to manufacture biodegradable plastic and no mass-manufactured products were generated through the research process, a notable outcome from the project was the lessons learnt/experience gained through the process of learning-by-doing and the systematic process of adopting, internalising and

Acronyms

A&AC	Agriculture and Agri-Food Canada
AMTS	Advanced Manufacturing and Technology Strategy
BEE	Black economic empowerment
CO_2	Carbon dioxide
CSIR	Council for Scientific and Industrial Research
DEH	Department of Environment and Heritage, Australia
DTI	Department of Trade and Industry
EU	European Union
IAM	Institute for Applied Materials
ICT	Information and communication technology
IF	Innovation Fund
IMS	Integrated Manufacturing Strategy
MCC	Magnesium Compound Consortium
N_2	Nitrogen
NRDS	National Research and Development Strategy
NRF	National Research Foundation
O_2	Oxygen
PLA	Polylactic acid
R	South African Rand
R&D	Research and development
SET	Science, engineering and technology
THRIP	Technology and Human Resources for Industry Programme
TNO	Netherlands Organisation for Applied Scientific Research
US	United States

1 Introduction

The South African government is centrally concerned with implementing and supporting programmes aimed at diversifying the economy away from its current dependence on natural resources into high-technology manufactures. Although South Africa is richly endowed with natural resources such as minerals, agriculture and energy, the advent of the knowledge-based society has highlighted that the availability of natural resources does not automatically confer a comparative advantage to a country rich in such resources. However, if the scientific knowledge embodied within the activities required to extract and process such resources is harnessed and broadened through local adaptation to suit other sectors, then resource endowments can be used a springboard for subsequent development. In addition, the further downstream a resource is processed, the greater the scope, potential and opportunity for diversification in high-value, non-resource-based, niche markets / applications.

The government recognises the important role that existing capabilities in the natural resource sector can play in the emerging system of innovation. Indeed, the fourth technology mission of the *National Research and Development (R&D) Strategy* (NRDS) emphasises "leveraging off resource-based industries and developing new knowledge based industries from them i.e. mobilising the power of existing sectors". Similarly, the DTI's proposed *Integrated Manufacturing Strategy* (IMS) aims at promoting knowledge intensity, value addition, and exports, and advocates the expansion of knowledge clusters and the continuous generation of intellectual property and new technologies to ensure future industrial competitiveness. These strategies have been followed by the *Advanced Manufacturing Technology Strategy* (AMTS), which aims to stimulate technological upgrading, facilitate the flow of technological resources to industry through new knowledge networks, and create an environment conducive to innovation through the supply of skilled people, technology infrastructure and funds. Sectors with the greatest potential to support the goals of the IMS and NRDS are prioritised, including advanced materials, product technologies, production technologies and information and communication technology (ICT) in manufacturing.

Despite this proactivity at the government level to provide an environment conducive to facilitating diversification, innovation and knowledge development in South Africa, there is a paucity of knowledge documenting how "know-how" and expertise at the firm level has emerged and evolved over time. In particular, understanding the factors that gave impetus to new product and process development, the type of human resources/absorptive capacities that facilitated it, the R&D process, the role of networks and collaboration, and the limitations that currently hinder the replication or advancement of such strategies is needed. Case studies are also needed that "unpack" the linkages and collaborative partnerships that were entered into to facilitate the diversification process in firms, particularly those that have moved from primary resource-based activities into high-value niche applications. In addition, understanding how capabilities and expertise in various areas have combined to assist in the migration of technologies from one industrial application/context to another are needed. Such information will go some way to ensuring that current government initiatives and programmes are well-targeted, appropriate and assist in fulfilling the broader challenges of science and technology development in the country in a sustainable and long-term manner.

This paper seeks to provide insight into these various issues by reviewing a THRIP-funded programme[31] undertaken between January 2002 and December 2004 focused

[31] The Technology and Human Resources for Industry Programme (THRIP) is one of a number of government-incentivised schemes currently aimed at facilitating technology and

around the production of biodegradable plastics from maize starch in South Africa. The case study is of interest and relevance for three reasons. First, while investigations into the manufacture of starch-based renewable plastics is not a new area of research, the South African experience involved the migration and adaptation of technological concepts and methodologies largely developed in Europe to meet the technological parameters and requirements of the local context. As such, the R&D process involved a combination of both basic "learning by doing" (local modification of existing thermoforming equipment and processes) as well as the systematic process of adopting, internalising and matching insights gained from interaction with international experts with those developed locally.

Secondly, it draws together three different, independent disciplines – food processing, polymer manufacturing and biotechnology – that became linked through two different research agendas; the need to broaden the application of a food product into niche applications, and to enhance R&D around polymers and polymer technology. Thirdly, the project involved, to varying degrees, a consortium of local and international research institutes, universities, manufacturing companies, and government organisations. Reviewing the various partnerships and linkages established between them is useful for formulating an understanding of critical issues involved in the innovation process such as the absorption capabilities of firms, how knowledge and technology is acquired, diffused and adapted, the importance of funding, the constraints involved in the innovation process, and how existing capabilities in other firms can be leveraged to ensure effective innovation, technology development, and product commercialisation in the future.

Before commencing with the local case study, the paper provides a brief review of the international experience of starch-based plastics and economic and environmental rationale for the move to manufacture bio-plastics and biodegradable plastics from renewable sources. The key features characterising the research endeavours of leading government organisations, research institutes and private companies will be discussed and the advantages and disadvantages of biodegradable starch-based plastics over conventional petroleum-based ones documented. Using this as a framework within which to situate the South African experience, a qualitative analysis of the manufacture of biodegradable plastics from maize starch in the country is then undertaken. The factors that led to the emergence of such investigations in South Africa, the different partnerships and networks that were established, the source of technology and funding, the outcomes of the research and constraints affecting the further development of knowledge and innovation in biodegradable polymer research will be assessed.

2 Biodegradable plastics from renewable sources: the international experience

2.1 The environmental and economic rationale

Plastics are relatively inexpensive materials used for a wide variety of applications in industries such as surgery, hygiene, catering, packaging, agriculture, fishing, environmental protection, technical and other sectors. Material characteristics of low-density, low cost, ease of processing and flexibility in design give plastics superiority over other packaging materials. Most plastics and synthetic polymers currently manufactured, however, are produced from petrochemical compounds and there is a

innovation in South Africa. It is managed by the National Research Foundation (NRF) and encourages the formation of collaborative partnerships between tertiary, private and public sector organisations and individuals.

growing global concern about the future economic sustainability of using such non-renewable inputs in such short-term applications. More importantly, conventional petrochemical-based plastics are not easily degraded in the environment due to their high molecular weight and hydrophobic characters. Consequently, the disruption caused to ecosystems as a result of non-degradable materials in the environment has prompted decision-makers and the plastics industry worldwide to identify and develop durable bio-based alternatives in an attempt to effectively dispose of waste plastics (Narayan, 1997; *Farmers Weekly*, 2000; DEH, 2002; A&AC, 2003).

Research into new product development in polymers is increasingly encompassing a holistic "life-cycle thinking" approach. The impact of raw material resources used in the manufacture of the finished product and the ultimate fate (disposal) of the product when it enters the waste stream is increasingly being factored into the product design and engineering process (Narayan, 1997). As a result of this, a considerable amount of investment and R&D has been conducted worldwide to identify alternative feedstocks that can be used to ensure the environmentally-friendly nature of plastic materials. The biochemical industry (food, grain, sugar) is regarded as offering the best solution to build capacity for biodegradable plastics at the expense of the petrochemical industry or, conversely, it is believed that the petrochemical industry could benefit from its long-standing experience in processing by leveraging its inherent capacities and technology to develop alternative, renewable feedstocks (Narayan, 1997; DEH, 2002). While the international community views biodegradable sources as an alternative to petroleum-based compounds, it is also acknowledged that it is only viable for specific applications due to the unique physical properties of some polymers used (Narayan, 1997).

2.2 Biopolymers and biodegradable plastics

In essence, there are two types of degradable plastics: photodegradable and biodegradable plastics. In the former, the polymer or the additives have light sensitive groups directly incorporated within them. Exposure to physical agents, such as light, results in the gradual breakdown of the polymer into smaller non-degradable pieces leading to a loss in the structural integrity of the material concerned. A type of polyethylene is currently being marketed that includes a catalyst that triggers the thermal degradation of the polymer. In contrast, biodegradable plastics are those that are capable of being completely decomposed into their organic constituents (carbon dioxide, methane, water, inorganic compounds, or biomass) by means of the enzymatic action of micro-organisms. While such processes can be measured by standardised testing procedures, factors such as the type of polymer used, the additives, fillers, weight of the product, bacterial environment, temperature, and degree of humidity strongly influence the time take for a specific polymer to degrade. Timescales can vary from a few months to a few years (FRIDGE, no date; DEH, 2002; A&AC, 2003).

In biodegradable plastics the core constituent is a renewable, natural resource. As such, they are often referred to as "biopolymers". The main sources of natural biopolymers include micro-organisms (bacteria, fungi), plants (crops, forests), and animals (livestock, insects, marine life such as shell fish and algae). Certain proteins and pectins have also been modified and adapted for use in biodegradable plastic production. The resins produced using these inputs can be converted into three types of biodegradable polymers: polylactic acid copolymers (these materials have a broad spectrum of properties but are largely aimed at applications presently held by polyesters, including fibres and packaging, and polystyrene); aliphatic/aromatic polyesters and polyester amides (while a wide range of property combinations can be obtained, these materials are generally aimed at applications held by polyethylene and polypropylene); and starch copolymers and derivatives (these are generally polyethylene and polystyrene replacements). The latter is the dominant type of biopolymer used (FRIDGE, no date).

2.2.1 Starch-based bioplastics

Starch, as a key component of many renewable raw materials, is becoming an increasingly important input to activities outside the food industry due to the variety of ways in which it can be modified. According to DEH (2002), starch is essentially a linear polymer (polysaccaride) comprised of repeated glucose groups linked by glucosidic linkages in the 1-4 carbon positions. The length of the starch chains varies according to the plant source but in general the average length is between 500 and 2 000 glucose units. There are two major molecules in starch – amylose and amylopectin. The alpha linkage of amylose starch allows it to be flexible and digestible. Starch-based biodegradable plastics may have starch contents ranging from 10% to greater than 90%. In the manufacture of plastics, starch may be used in three ways: as an adjunct to conventional plastics (6% starch); blended with synthetic polymers (60-70% starch); and as a thermoplastic (75-95% starch) (FRIDGE, no date). In order to be suitably biodegradable, the starch (amylose) content in such polymers needs to exceed 60% before significant material breakdown occurs. As the starch content is increased, the polymer composites become more biodegradable and leave less recalcitrant residues.

Often, starch-based polymers are blended with high-performance polymers (e.g. aliphatic polyesters and polyvinyl alcohols) to achieve the necessary performance properties for different applications this, however, influences the ultimate degradability of the plastic. Biodegradation of starch based polymers is a result of enzymatic attack at the glucosidic linkages between the sugar groups leading to a reduction in chain length and the splitting off of sugar units (monosaccharides, disaccharides and oligosaccharides) that are readily utilised in biochemical pathways. High-starch content plastics are highly hydrophilic and readily disintegrate on contact with water. At lower starch contents (less than 60%) the starch particles act as weak links in the plastic matrix and are sites for biological attack. This allows the polymer matrix to disintegrate into small fragments, but not for the entire polymer structure to actually bio-degrade (DEH, 2002).

Although the principle source of starch-based biopolymers varies across countries depending on the main source of carbohydrate available, generally, the main sources are corn/maize, wheat and legumes (United States, Australia), and potatoes (Europe). Other sources being explored include cassava (Thailand, India), and tapioca (Japan) (see Sriroth, 1997; Balagopalan, 2000; *Farmers Weekly*, 2000; CGPRT, 2003; Sun and Jianfeng, 2003; Greene, 2005).

Biopolymers can be used for a vast range of applications. While initial research efforts in the 1980s focused primarily on the use of polylactic acids in disposable packaging, agricultural film, and high-end medical applications (implants, sutures, slow-release drug delivery systems), more recent research has extended the market applications for bioplastics to include non-biodegradable products, such as apparel and textiles, which can be either recycled or incinerated (Table 7).

Table 7 - Market applications for bioplastics (A&AC, 2003, 10)

Biodegradable		Non-biodegradable
Packaging: ▪ Packaging bags and films ▪ Composting bags ▪ Loosefill packaging ▪ Edible packaging	Horticultural: ▪ Mulching films ▪ Greenhouse films ▪ Plant pots ▪ Soluble bags for plant care products	Apparel: ▪ Sports, active wear, and underwear ▪ Fashion blends with wool, silk and cotton
Objects often left on the ground: ▪ Golf tees ▪ Disposable dishes ▪ Firearm ammunition wads or shells ▪ Firework casings ▪ Cemetery decorations	Medical applications: Capsules ▪ Resorbable implants ▪ Suture threads, clips ▪ Orthopaedic fixations (e.g. screws, pins) ▪ Anastomosis ring ▪ Ligature clips	Textiles: ▪ Carpets ▪ Comforters ▪ Pillows
Eco-marketing/aesthetic: ▪ Hydro-soluble bags for baits ▪ Bank card ▪ Watch case ▪ Ball point pens, toys, gadgets		

A number of companies are now producing starch-based plastics throughout the world including Biotec GmbH (Germany), VTT Chemical Technology (Finland), EverCorn, Inc. (US), Novamont (Italy), EarthShell (US), AVEBE (US), Rodenburg BioPolymers (Netherlands), StarchTech, Inc. (US), and Vegeplast (France). The main player in Europe is Novamont, which owns 80 patents and related extensions. Rodenburg BioPolymers (Netherlands) has built a plant to transform potato wastes generated by the french fry industry for use in injection moulding. The plant capacity is said to be 36,000 tonnes per year. Its targeted markets include golf tees, controlled release fertilizers, combinations with paper, and temporary protection of engine openings (A&AC, 2003; Focke, 2003; FRIDGE, no date).

In addition to their biodegradable potential, another important environmental benefit associated with substituting synthetic petrochemical polymers with biopolymers is its contribution to reducing greenhouse gases. It is estimated that starch-based plastics can save between 0.8 and 3.2 tonnes of CO_2 per tonne compared to 1 tonne of fossil fuel-derived plastic. The range reflects the share of petroleum-based copolymers used in the plastic (*Farmers Weekly*, 2000; DEH, 2002). From an economic/industrial perspective, shifting towards the manufacture of bioplastics can also assist in diversifying agriculture out of food production. With each successive level of processing a raw material is subjected to, the scope and opportunities for use in a diverse range of downstream applications increases. Beneficiation not only increases the value of the original input, but assists in ensuring the sustainability of the industry in the long-term.

Furthermore, much of the manufacturing process and machinery used in making bioplastics is based on food science and food production techniques. Bioplastics and biodegradable synthetic polymers can be produced using existing plastic processing machinery, including thermoforming, various types of injection moulding, compression moulding, extrusion (films, fibres), and extrusion coating and lamination (DEH, 2002; A&AC, 2003). Leveraging off existing capabilities and know-how and laterally migrating them into other applications in this way not only contributes to reducing the costs of having to purchase new pieces of equipment but also helps to increase the rate of industry take-up and the diffusion of technology.

Biodegradable plastics are gaining market momentum around the world. Polymers made from renewable resources, particularly those derived from starch and sugar, are expected to account for 60% of the market for European Union (EU) biodegradables in 2010. By 2020, the share of polymers using conventional petroleum-based compounds are expected to only comprise 20-30% of all plastics manufactured in the EU. In the United States, the replacement of non-degradable plastics with biodegradable, renewable alternatives is also expanding although it is largely driven by traditional economic drivers such as price and performance (A&AC, 2003).

Despite this worldwide trend, there are a number of drawbacks associated with biodegradable plastics. Chief amongst them is bioplastics' low water solubility. Starch is hydrophilic and partially water-soluble. Articles made from starch lose their mechanical properties in humid environments and disintegrate when placed in contact with water. Corn starch plastic is also weaker and difficult to make transparent. Starch, moreover, in its native form is not thermoplastic. When untreated starch is heated, thermal degradation occurs before the starch melts and flows. Therefore it cannot be easily processed like conventional plastics. The degree of processing the starch has to undergo before it becomes useful considerably increases the cost of the finished product. Indeed, the cost of the finished product relative to other plastics makes it a deterrent to widespread production, particularly in less developed and less affluent societies. In a review of 170 international biodegradable polymer patents it was noted that the second generation polymers have been estimated at approximately 20% higher price, (Symphony/ EPI technology) than the commodity polymers typically used in packaging applications (FRIDGE, no date).

The industry is currently working toward bringing down the cost of manufacturing biodegradable polymers by increasing production capacity, improving process technology, and using low-cost feedstocks. A number of new starch-based technologies and advances are also being made in order to improve the performance of the material. Methods that are being researched in an attempt to improve the water resistance of starch include starch laminated films; using expanded bead technology to make starch foamed trays; and developing starch-fibre composites. Starch can also be "complexed" to form a variety of plastic products with differing performance properties. According to Novamont (Italy): "the specification of the starch, i.e., the ratio between amylose and amylopectine, the nature of the additives, the processing conditions, and the nature of the complexing agents allows engineering of various supramolecular structures with very different properties" (Pandley et al., 2005).

The use of nanotechnology is also being investigated. An EU consortium (called Bionanopack) involving eight organisations from Italy, Germany and Greece are developing nanocomposite food packaging using starch and clay. According to the Netherlands Organisation for Applied Scientific Research (TNO), "The overall aim of the project is to develop a new biodegradable food packaging material with low permanent gas (O_2, CO_2, N_2) and water permeability. The structure of the new material is based on homogeneously dispersed silicates (clay minerals) in thermoplastic starch obtained via polymer melt processing techniques." The consortium is being coordinated by the Institute of Industrial Technology, TNO, Eindhoven (Netherlands). The resultant nanocomposites produced can be used for a variety of different applications. Nanocomposites of this category are expected to possess improved strength and stiffness with little sacrifice of toughness, reduced gas/water vapour permeability, a lower coefficient of thermal expansion, and an increased heat deflection temperature, opening an opportunity for the use of new, high performance, lightweight "green" nanocomposites materials to replace conventional petroleum-based composites (Pandley et al., 2005).

It is important to note that most research and development programmes undertaken around the world with regard to innovating, developing and commercialising new biopolymer products and processes are undertaken in partnership or as part of a consortium. Partners include research organisations, tertiary institutions, shopping outlets, industrial conglomerates, manufacturers, and private firms. Networks extend locally and internationally and funding is usually shared amongst participants and outside government resources are often drawn upon. The degree of funding in such programmes is also substantially high – for example, in the STARPLAST research project, part of the Competitive Industrial Materials from Non-Food Crops LINK Collaborative Research programme, funding was provided for a duration of three years and amounted to GBP1 million, of which 50% was provided by research groups and the British government and 50% by industry. Furthermore, the time lags taken between the research and final commercialisation stage are significant (DTI UK).

Against this review of starch-based biopolymers and the nature of research activities undertaken abroad, the discussion now shifts to explore the South African experience of maize-based plastics which culminated in a THRIP-funded collaborative project in the late-1990s.

3 Starch-based plastics in South Africa: the THRIP project

Between January 2002 and December 2004 a collaborative project was undertaken in South Africa to develop and commercialise a biodegradable plastic using starch produced from maize as its principal feedstock. At the core of the project were three key institutions – the Centre for Polymer Technology (a division within the Council for Scientific and Industrial Research, CSIR), the Institute of Applied Materials (IAM, a research centre in the University of Pretoria) and African Products (Pty) Ltd. (the largest wet-mill producer of maize starch in Africa) – which provided the framework and agenda for the research. Through personal interactions and relationships established between members of these core institutions with other interested individuals and organisations, both locally and internationally, a series of additional linkages were fostered that were fundamental in broadening the scope of the project and providing critical inputs and know-how to enable technological learning and innovation to take place.

3.1 Origins of the research programme

The initial impetus for the emergence of the collaborative project can be traced back to three separate research agendas undertaken by various organisations and individuals that coincided in the early 2000s. Although no previous joint investigations between academic institutions and private enterprises had been made into exploring the possibilities of producing biodegradable starch-based polymers in South Africa prior to the commencement of the project, research into polymer compounds was well-established, particularly at the Centre for Polymer Technology at the CSIR in Pretoria. During the 1980s, two academics, both of whom would prove instrumental in establishing the research partnership, were employed at the Centre. Although one of the researchers subsequently left the CSIR to pursue his research interests independently, he retained contact with his colleague and kept abreast of developments at the CSIR. His independent research endeavours encompassed establishing his own manufacturing and R&D company, Xyris Technology CC, and undertaking exploratory visits overseas to broaden his understanding of the European experience of polymer research, specifically the manufacture of biodegradable plastics.

He visited most of the leading companies and organisations involved in such research and established commercial contacts and linkages with some of the principle scientists. In 1996 he was appointed director of the Institute of Applied Materials (IAM) in the Department of Chemical Engineering at the University of Pretoria with the brief to establish a research institute that did collaborative and consultative work. His previous experience at the CSIR in polymer compound technology and in establishing a manufacturing business meant that he was well positioned to fulfil the brief and engage with other organisations involved in such research.

Within the CSIR, research into polymer compounds continued throughout the 1990s. Investigations extended into the possibility of replacing non-renewable petroleum feedstocks used in conventional plastics with natural, renewable alternatives. The viability and use of biodegradable fillers in packaging were explored as well as compostable plastic shopping bags. A key environmental question that emerged in South Africa in the late-1990s was the issue of non-biodegradable plastic bag disposal. Plastic bags constituted about 7% by mass of municipal waste in the country and were a very visible form of litter (Mail & Guardian, 2003). An inquiry was led into the feasibility of switching to photo-degradable and biodegradable alternatives (see FRIDGE). The CSIR was involved by virtue of its research into polymer compounds. Involvement in the development of an alternative environmentally-friendly plastic bag was seen by the CSIR as a key research agenda and an opportunity to not only advance research and knowledge in the area, but to utilise available laboratory equipment to produce and commercialise a product with a distinctive social and environmental benefit.

Within this broader research environment, a leading local producer of maize starch and derivatives, African Products, was exploring alternative downstream market applications for its products. Various possibilities were investigated including paint thickeners. However, the end use of starch in such applications was considered too expensive relative to other alternatives and the quantity produced. Consideration was therefore given to the possibility of entering niche "green" applications that would add value and would off-set production costs. Further, with rising oil prices, the attractiveness of starch as a replacement feedstock for petroleum-based plastics was increasing. The possibility of developing a cheap, biodegradable plastic derived from maize starch in South Africa was raised. Recognising that its research laboratories were unsuited to the development of plastics (R&D was mainly concentrated around food technology) and that it also lacked expertise in polymer compounds, African Products embarked on a strategy to establish links with other organisations capable of developing the concept further (Godfrey, 2005). One of these links was with the CSIR. African Products approached CSIR to explore alternative uses and markets for its starch products, particularly the production of an injection mould compound that was cheaper than conventional plastics, compostable, and suitable for a large (preferably overseas) market. The CSIR subsequently became the research partner as well as the project manager in the project (Godfrey, 2005). The CSIR, in turn, approached the IAM at the University of Pretoria to participate in the project due to its long association with the director.

3.2 Key features of the project

The guiding objective of the project was to develop and commercialise a starch-based plastic without the use of significant amounts of synthetic polymers. The resultant product needed to be relatively cheap and easily processable using existing plastics conversion equipment. The technical focus of the study was to improve rheology (melt flow characteristics) to the extent that the material could be processed on conventional injection moulders. Various additives that improve the water resistance of the biodegradable plastics were also to be evaluated (www.csir.co.za).

All three of the core participants recognised the potential micro- and macro-level benefits that would be gained by the efficient pooling of knowledge, capabilities and resources in the fulfilment of the project mandate. At the macro level, the spin-offs that would result would be medium to long term in nature and would encompass a social, environmental and economic dimension. The most important benefits would parallel those advocated by the international community: the efficient disposal of waste products; the replacement of a non-renewable input with a renewable, biodegradable one; and diversification away from primary agricultural production into advanced manufacturing. At the micro-level, the benefits would be specific to organisations involved. For the IAM and Centre for Polymer Technology, the benefits would largely be in the development of new knowledge (by students and staff) in advanced materials and the fulfilment of the directive to form collaborate partnerships outside the university. In the case of African Products, benefits would include not only the development and commercialisation of a new product that would be give them international competitiveness and provide the foundation for the establishment of partnerships overseas, but would also assist in the diversification of the company's product base and support its role as an environmentally-conscious firm.

3.2.1 Sources of technology, migration and learning

As evident from the earlier discussion of the international experience of bio-polymer and biodegradable plastics research and development, starch-based plastics is not a new area of inquiry. However, in Europe the base starch used is potato rather than maize, so the chemical challenges presented to the consortium were somewhat different to those undertaken overseas. Furthermore, until African Products approached CSIR with the proposal of diversifying starch into plastic manufacture, the level of product-related R&D in biodegradable plastics was reserved to a few key areas, most notably plastic bags and fillers.

A key outcome of the inquiry into the feasibility of switching to biodegradable plastic bags in South Africa was the high production costs, which negated against its widespread introduction (FRIDGE, no date). Researchers at the IAM realised that the commercial implications associated with developing starch-based plastics would be one of the greatest challenges that would have to be overcome in order for it to be viable in the long term. While starch on its own was cheap (R2 per kilogram compared to R10 per kilogram for plastic), and existing extrusion machinery could be used, the finished product would be considerably more expensive given the additional stages of processing needed to convert the maize starch into a product with the same material characteristics as conventional plastics. In order to be commercially viable, therefore, the final method selected would have to produce compostible plastics relatively easily and with high value.

The insights gained from the IAM's director's previous investigations in Europe, particularly in Germany, Italy and the Netherlands, regarding the best approaches to the manufacture of biodegradable plastics proved invaluable in setting the technical parameters of the project. Drawing on existing technology and research was seen an imperative to fulfil the criteria of the project and enable the pursuit of niche markets. In this regard, one of the key technical inputs came from the IAM's interaction with the TNO, the Dutch equivalent of the CSIR. The TNO, together with its partner university, had made great strides in polymer plastic technology. The TNO had found a way to produce biodegradable plastics relatively cheaply by using waste potato peels. Motivated by the need to find a way of disposing significant quantities of waste peels following a decline in demand for red meat and hence a drop in fodder requirements in the country, researchers in the Netherlands developed a process that combined the waste starch in the potato peels with synthetic polymers to develop a biodegradable plastic.

Polymer technology research at the TNO was also being extended to the development of new synthetic products, coatings and polymer materials capable of meeting special requirements imposed by industry, specifically those relating to protection, sustainability, decoration, providing a barrier effect against gases, corrosion resistance, electrical conductivity or luminosity. In order to achieve these effects, experiments were being conducted that combined plastics with metal, glass or ceramics at a macro (fibre-reinforced plastic), micro (coatings) and nano (biodegradable plastic) scale (www.tpd.tno.nl/; van Velzen, 2004; Padley et al., 2005).

The TNO's research into nanoclays was particularly interesting to the IAM as the applications were in niche applications (polymer electronics, coatings, membranes and environmentally friendly solutions for crop protection). The TNO had also undertaken research into the use of nanoclays in the production of water resistant films (which could withstand water for three months before degrading) which was of particular interest to local researchers given the prevailing debates around the issue of effectively managing and disposing of plastic bags. The TNO had also developed proprietary technology to disperse nanoceramic particles in a wide range of polymeric (coating) materials, which offered potential benefits in the injection moulding of investment castings. The TNO's knowledge of polymer materials, special processing steps and functional product requirements provided the basis for South Africa's commencement into the development new polymers and hybrid materials for products for niche, high-value markets.

Given the long history of polymer research in South Africa and the capabilities that had evolved in the two research organisations there was a base upon which many of the ideas gleaned from interaction with international experts could be transferred (i.e. "migrated") and internalised. While interaction with international research organisations was critical for establishing the main hypotheses, methodologies and technical parameters for the project, there were a number of differences with the approach adopted by the South African team that necessitated a considerable amount of "learning by doing", systematic local adoption and internal product innovation. In the first instance, the project used maize starch as the principal renewable input. Corn starch is used widely in the United States in the manufacture of biodegradable plastics, however, it is generally converted (by fermentation) into polylactic acid (PLA) before being processed further. In South Africa, maize is the dominant carbohydrate crop; however, it is not directly suited to the manufacture of plastics due to the low amylose content. A starch has to have an amylose content greater than 60% in order to be used without the addition of a synthetic polymer compound. Consequently, starch containing enhanced levels of amylose had to be imported in order for the project to commence. African Product's association with Penford Australia Ltd (a subsidiary of Penford Corporation, a US supplier of speciality starches), however, provided the consortium with access to a variety of maize – known as Hi-Maze – with a sufficiently high level of amylose to undertake process-related research without prior fermentation (www.penford.com.au).

Secondly, one of the objectives of the project was to evaluate the use of various additives to improve the water resistance of the biodegradable plastics. The use of nanocomposites in polymer production was therefore a core area of interest given their ability to improve the material properties of the resultant plastics, particularly in terms of rigidity, strength, and barrier characteristics. Nanocomposites could also assist in maintaining a level of transparency. The types of nanocomposites that were experimented with during the project were broadened to include hydrotaclite, largely as a consequence of the interest expressed by the Magnesium Compound Consortium (MCC) for the use of such composites in investment castings.

While the project drew extensively on the work done abroad, no licensing agreements were entered into although visits from international scientists did take place. Most of the adaptation and R&D was done locally and drew on the expertise and know-how of the various scientists and researchers at the IAM and the CSIR. As an interdisciplinary materials research group, the IAM has a high-level skills base encompassing physicists, chemists, chemical engineers, material scientists, and metallurgists with a range of technical and application experience. A similar skills base is available at the Centre for Polymer Technology. At the IAM, approximately two PhD and two Masters degrees were generated during the project and various undergraduates were involved in the nanocomposites research. At the CSIR around six people were involved to varying degrees in the project.

While existing facilities and polymer extrusion equipment at the CSIR were used throughout the duration of the project, a certain degree of know-how was needed in order to ensure the material was suitable for use on conventional machinery. While it is widely asserted that existing production techniques can be used to produce biodegradable products, initial tests undertaken at the CSIR highlighted a number of difficulties associated with extrusion using conventional thermoforming machinery. In particular, slower blowing rates, difficulties in maintaining thickness, and reduced material strength were encountered (FRIDGE, no date).

3.2.2 Funding

In terms of funding, various sources were approached by the three leading partners prior to the commencement of the project. A proposal was first submitted to the Innovation Fund. The Innovation Fund (IF) provides resources for technologically innovative R&D projects that will not only generate new knowledge, but also widespread national benefits in the form of novel products, processes or services (www.innovationfund.ac.za). The application, however, was unsuccessful. The main concerns raised by the NRF related to the commercial risks associated with the project and the fact that there was no clear information to show how the project would result in revenue generation, black economic empowerment (BEE) and job creation. An attempt was also made to obtain EU Funding (5th Framework) to take research into plastic film development further (blow film is used in the manufacture of plastic bags). Given the highly competitive nature of the funding programme, the application also failed (according to one of the participants only 14% of the EU programmes applied for were successful at the time of the enquiry). African Products then suggested that the project parameters should be refined and the scope reduced and that they try the government incentivised Technology and Human Resources for Industry Programme (THRIP). Four proposals were submitted to the National Research Foundation (NRF) over a space of two years before funding was secured for a three year research period. An extension of one year was also granted. THRIP funding enabled the IAM to go into an equal partnership with the CSIR.

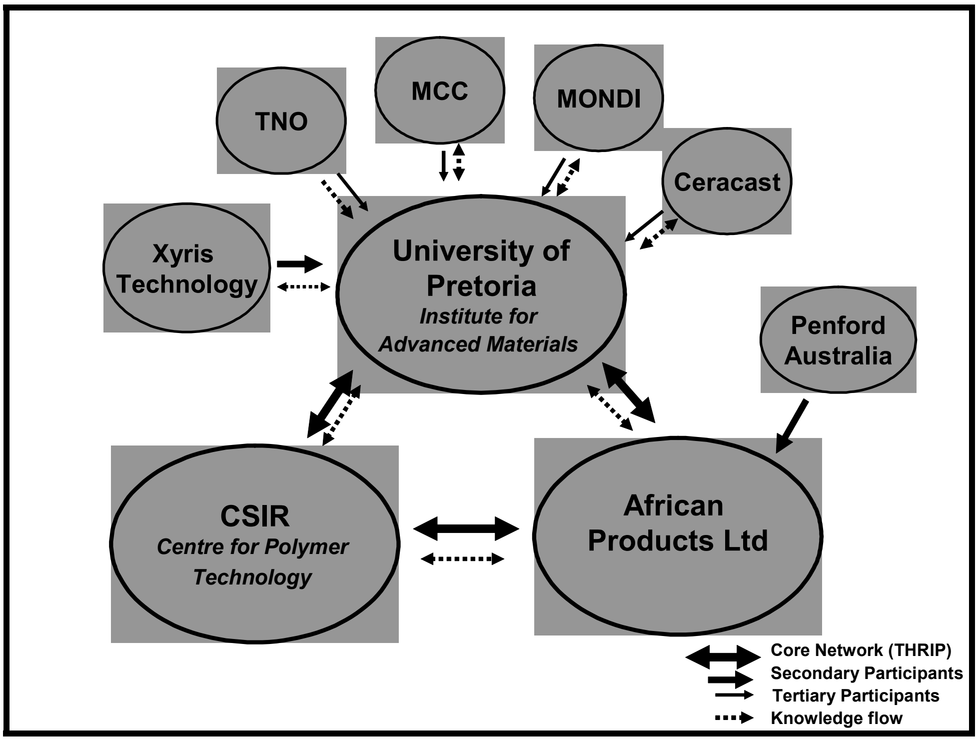
The THRIP is managed by the NRF. The basis of the programme is that for every R2 invested by the private sector in a science, engineering and technology (SET) project, R1 is provided by the NRF. This can, however, vary according to the project being undertaken. The main criteria that had to be fulfilled by the consortium in order to secure funding were threefold. First, the project leader and project had to be based at a higher educational institution or Science Engineering and Technology Institution (SETI). Second, the research had to be of a high standard, have clearly defined technology outputs, and involve at least one higher education institution and one industrial partner. Third, at least one registered South African student had to be involved in and trained through the research for every R150 000 of THRIP investment provided (http://www.nrf.ac.za/thrip). CSIR acted as both the project manager in the project and the intermediary between the various participants. African Products and Xyris Technologies, as the two private enterprises involved in the project, contributed approximately R400 000 to the project, of which the largest share (R300 000) came from African Products (Godfrey, 2005). The balance was provided by THRIP in three instalments – R381 000, R327 000 and R260 000.

While the resources provided by the industry partners and the THRIP enabled the project to commence, problems were encountered during the application and funding process. The participants found the application process very time-consuming and lengthy. Funding was only secured after the fourth attempt and after two years of trying. Moreover, the researchers felt constrained by the parameters and timescales imposed by the funding programme. The lead researchers argued that researching, developing and commercialising products such as biodegradable plastics requires long timeframes and progress is often difficult to predict. Frequent modifications, testing and trials slow down the process, particularly as the composting rate of the plastics being designed extended from anywhere between a few weeks to a number of months. Participants argued that while in hindsight more accurate planning at the commencement of the project may have prevented some of these problems from arising and enabled the commercial benefits to be realised earlier, a more flexible approach to funding would have been more beneficial given the nature of the research project (Godfrey, 2005).

3.2.3 Partnerships and networking

Partnerships and networking underpin the project and provide it with an element of vibrancy and dynamism. They also played a critical role in advancing knowledge in the area of bio-based polymers in South Africa. The starch-based plastics network is complex, both in terms of the number of partners involved and the extent of their involvement (Godfrey, 2005). The primary (core) set of relationships are between the three THRIP partners (the IAM at the University of Pretoria, the Centre for Polymer Technology, CSIR, and African Products (Pty) Limited, based in Germiston). Within this formal network there are two core sets of relationships which extend back to the 1980s and 1990s. One is between the IAM and the CSIR Polymers Technology group, the other between the CSIR and African Products. Both of these rely heavily on personal interaction for their success. A very important link exists between Xyris Technology CC (a sponsor of the research) and the University of Pretoria. Xyris was founded by the director of the IAM before he joined the University and the company is interested in commercialising the final research results. The relationship between the IAM and TNO was vital for providing the technological focus of the project. The long-standing relationship between African Products and Penford, Australia was also crucial for providing a source of suitable starch feedstocks needed for the manufacture of the plastics. Both these latter three sets of relationships can be termed "secondary relationships". A third (tertiary) level of partnerships exists in the network. The IAM also has linkages with a number of local private companies interested in polymer compounds (although not specifically starch-based) and the commercial opportunities that could arise from the research. These include the Magnesium Compound Consortium (MCC), Mondi, and Boart Longyear Ceracast. A brief description of some of these affiliated organisations and companies and their contributions to the project will be elaborated below and are highlighted in figure 9.

Figure 9 - Participants involved in the network and their relationship to each other



African Products and Penford, Australia

African Products, which initially belonged to Tate & Lyle in the 1970s, was sold to Anglo American in the late 1970s. It was bought by Tongaat in the 1980s. It is a wholly-owned subsidiary of the corporation and has been the second-largest contributor to profits (after Tongaat's sugar division) for the last four years (*Engineering News*, 2003a, 2003b). African Products entered the maize starch plastics project as an exploratory exercise; using the experience it had already developed with the CSIR to establish additional downstream markets for its products. African Products was interested in eventually working on a large scale. The project was therefore of great interest to African Products as it not only give them the possibility of utilising their starch in other niche areas (particularly for the international market), but that the final product was biodegradable. However, in order to be commercially viable, 100,000 tons of the base compound had to be produced per year to warrant setting up an injection mould plant. Although investment in the project was viewed by African Products as a risk venture with potential commercial benefits (Godfrey, 2005), their role in the broader project was very important. Not only were they a principal financier, but played an important role in the sharing and dissemination of knowledge. Two people from the R&D department at African Products worked with the CSIR on the project.

Moreover, African Products' relationships with other international companies involved in the production of maize starch were also of significant value to the project. African Products has a technical licence agreement with Corn Products, of the US, one of the three largest wet millers in the world. More importantly, it has an agreement with the US-owned Penfords of Australia. The company produces modified starch, particularly waxy maize starch modified products. Penford Australia was instrumental in developing the first seed crop of Australian-grown high amylose corn in the 1970s – HiMaize). Penfords was African Products' agent in Australasia and African Products was Penfords' agent in Africa (www.penford.com.au).

IAM, MCC and Boart Longyear Ceracast

The Magnesium Compound Consortium (MCC) and Boart Longyear Ceracast are research partners, but are not directly part of the THRIP agreement. Both are looking for particular polymer compounds that may arise from the maize-based starch research, which could facilitate the development of new products using their existing manufacturing techniques.

The Magnesium Compound Consortium (comprising Chamotte Holdings, Altona Chemicals, University of Pretoria, Pretoria Technikon and one private individual) is based in Chamotte Holdings, Midrand. Chamotte Holdings is primarily a mining company operating a magnesite (magnesium carbonate) mine near Malelane and chalk mine near Baberton, Mpumalanga. The magnesite is used to produce several grades of magnesium oxide and magnesium sulphate, which is supplied in bulk as commodity chemicals. The MCC is funded by the NRF and involves nine or ten researchers at any one time (Godfrey, 2005). The THRIP consortium became involved with the MCC through the IAM, which became interested in the MCC's investigations into the possible synthesis of magnesium hydroxide, hydromagnesite and, specifically, hydrotalcite. Hydrotalcite is an additive to plastics and MCC is investigating ways in which to can replace toxic heavy-metal salts currently used as heat stabilisers in plastics manufacturing (Engineering News, 2003c). The IAM was exploring the use of hydrotalcite (an anionic clay) as a nanocomposites in the production of biodegradable polymers and thus approached the MCC into acquiring hydrotalcite samples when Chamotte Holdings goes into production. Although no formal network exists, ideas are traded between the MCC and the IAM and, consequently, the rest of the THRIP network.

Boart Longyear is a member of the Anglo American group and is a leading supplier of products, processes and services to the natural resource, construction, quarrying and other industrial sectors both locally and worldwide. Boart Longyear Cerecast was established in 1984, and is situated in Postmasburg, South Africa. Ceracast was one of the first companies to start manufacturing precision castings for specialised applications in South Africa, particularly in the mining industry (e.g. coal borers, taper bit bodies, jackhammer components, conveyor belt scrapers). In 2003 the decision was taken in Ceracast to move into wax-processed castings as a means by which to broaden their customer base and diversify their product range. The company had traditionally used a plastisol process. Ceracast is currently one of only two casting plants in the world that uses and manufactures urea as well as wax as a moulding material (*Engineering News*, 2005). Ceracast became involved with the THRIP project through its interest in exploring ways in which the waste materials from ceramic formulations could be used in the production of degradable starches, particularly in coatings. Such research has been explored extensively at the TNO. Collaboration between Ceracast and the THRIP consortium is in its early stages.

IAM, CSIR and Mondi

Mondi, one of the leading paper manufacturers on the continent, is another Anglo-American owned company with whom the network is working. Mondi's interest in the project stems from the potential commercial benefits that could result from the successful development of a biodegradable plastic. The company had an initial agreement with the project team for the production of compositible seedling trays, which were the first marketable products to be produced by an IAM student in the CSIR laboratories. Mondi also expressed interest in the manufacture of disposable packaging for specialised applications that only degraded after a certain period of time. One of the problems experienced by the company in the European market was the low rate of water permeability of the packaging products produced. In order to withstand the climatic conditions of the region such products, particularly paper bags, would have to be coated with a plastic layer that was impermeable in the short term but could be totally recycled as paper. When paper contains more than 5% plastic it is recycled as "mixed plastic" in Europe, whereas if it contains less than 5% plastic it can be recycled as paper. The research group's interest in developing coatings for paper bags and advancing paper towards plastic film properties (and association with the TNO where such technology was available to achieve this) was therefore seen as potentially beneficial to Mondi. For the research group, interaction with Mondi would provide access to an international market for its products, particularly as the South African market was regarded as being too small to sustain the scale of commercialisation needed to make the project feasible in the long-term. Mondi already had access to overseas markets which could be used and leveraged in order to secure and broaden the commercial scope for new applications (Focke, 2003).

<u>IAM and Xyris Technology CC</u>

Xyris Technology CC was established in 1990 and is a small custom plastics additive compounder in Bashewa, South Africa. The company's product line includes flame-retardants, corrosion inhibitors, barrier additives and purging compounds. Xyris Technology has been involved in polymer related research for a considerable length of time, including the development of technology for the controlled photodegradation of polyethylene and polypropylene. The director of the company is closely affiliated with research and development work related to biodegradable plastics at the IAM at the University of Pretoria (www.xyris.co.za). The company's main aim is to use these materials for manufacturing sapling pots and producing a cost-effective material suitable for film blowing. In terms of its involvement in the consortium, in addition to its financial contributions, Xyris Technology CC is poised to become the applications partner. Although it currently lacks the capacity to produce products of the quantity envisaged by African Products, these details will be negotiated once a suitable compound has been developed (Godfrey, 2005).

In terms of the success of the networking, partnerships and interaction has facilitated knowledge sharing and the dissemination of know-how and expertise in specific areas. Godfrey (2005) points out that knowledge transfer between the partners is regular and intensive. One way in which the dissemination of information and ideas occurred was via the informal interaction between staff, students and project leaders. Knowledge transfer also occurred through the frequent ad hoc meetings at the CSIR (mainly to discuss the work and the direction of research), the formal quarterly meetings of the core partners (at which the organisation of work and research progress was monitored), and the bi-annual formal meetings with peripheral partners. A high level of trust and mutual respect underpins the relationships between the various participants as all are bound by the need to develop a technology and product which cannot be developed in isolation (Godfrey, 2005). The nature of such relationships ensures the flexibility of the network and the general lack of conflict or tension. Godfrey (2005) points out that another factor that has reduced the importance of formal agreements, particularly with regard to intellectual property rights, is that the research is not yet close to producing a product that can be commercialised.

The relationships in the network were also shaped by the requirements and conditions of THRIP (Godfrey, 2005). While the core members of the consortium are senior personnel, the involvement of students and researchers at different levels has ensured a broad base of exposure to the research objectives and methodologies. It is clear that trust, ability and hard work have been critical to the effective function of the consortium. Active networking begins among colleagues at work, and is slowly developed with other colleagues at outside institutions and may take years to consolidate. Felicitous meetings and timing also play an important role in putting the 'right' people in contact at particular times (Godfrey, 2005).

3.2.4 Results of the study

The primary objective of the research project was to commercialise a suitable biodegradable plastic from maize-starch. Although this objective had not been reached at the end of the funding programme, participants in the project assert that significant advances had nevertheless been made and that most (80%) of the key milestones had been reached. In terms of meeting African Product's objectives of finding niche applications for maize starch, two products were successfully developed and the research team is still looking into a third. Polymer compounds developed and under trial using equipment and laboratories at the CSIR include seedling trays, pot plant holders, food containers, and golf tees. The focus of the project has now shifted to the commercialisation of a product that would be economically viable to produce.

Researchers assert that in assessing the outcomes of the project consideration should also be given to a number of additional spin-offs which resulted during the course of the R&D process and testing stage. These have implications for the future success of the project. In the first instance, a food store has expressed interest in replacing the polystyrene currently used for packaging with a biodegradable product and is prepared to pay a premium for an environmentally-friendly product. Such interest has motivated the research team to continue its R&D endeavours (Godfrey, 2005). In addition, Sappi (the world's largest producer of coated fine paper) is interested in the possibilities offered by the seedling tubes being developed by the IAM and CSIR. Such products could be of significant economic value in the future as the company loses a sizeable percentage of young saplings annually. It is alleged that protection afforded to the young seedling by encasement in biodegradable tubes would boost survival rates. The challenge, however, is to develop a tube that can degrade fully within 3 and 6 months. In addition to improving the materials of the tube, current research by the research group is also focused on developing a root pruning system to assist in the growth process and trials are in the advanced stage. Tests are still being run on new coating compounds (modified hydrotalcite calsys) and the MCC and Ceracast are still interested in the commercial possibilities of the product in injection moulding. Scale-up trails are being conducted with the moulding compounds and commercialisation is envisaged for 2006.

Another important spin-off that resulted from the project was the advancement of capabilities and know-how in the area of polymer technology and materials science. In particular, knowledge transfer occurred between the various researchers involved in the various aspects of the innovation process and new areas of expertise were developed, specifically amongst students and young graduates at the CSIR and IAM. Knowledge sharing also existed with the African Products team which met with the CSIR every two months in order to discuss the developments of the project. Results and experiences were documented in research reports, dissertations, theses, journal articles, and presentations at conferences and disseminated to a wide range of international and local scientists and researchers.

Researchers involved in the project assert that there were three reasons why the project failed to reach the commercialisation phase. First, the technology is still at an early stage of development and more money and time would have to be invested to make it viable. Second, the aging problem of the starch requires the addition of expensive additives which raises the cost of the finished product. Thirdly, African Products lost the licence for Hi-Maize. Access to a source of competitively priced raw material inputs was one of the main reasons why the project was able to commence. The only starch that produced the results required by the team was Hi-Maize, which was acquired through African Products' association with Penfords. The loss of the licence agreement towards the end of the project meant that the high costs of acquiring this raw material from elsewhere (e.g. National Starch) would make the final products uneconomical for the mass market. According to African Products, the reason they lost the licence was the high cost of importing the Hi-Maze starch as well as the lack of demand for the starch. There was not enough demand within South African to cover the cost of purchasing the Hi-Maze starch and this made holding on to the licence very expensive for African Products and as a result they relinquished the licence as well as their participation in the project. However, African Products still maintains a relationship with the CSIR on other projects. The current emphasis of the project is on the development of niche markets.

The participants also raised the issue of access to a continuous source of funding as a constraint to the future commercialisation of the R&D endeavours. Obtaining alternative sources of funding is complicated for projects like this one which rely heavily on staff and students at research universities for their success. The criteria placed on various participants cannot always be met (Godfrey, 2005). At the same time, having already tried the Innovation Fund and drawn on THRIP support, the researchers are not sure where future investment will sourced.

Consideration of the implications of these factors is critical for ensuring the continuation of research efforts in this area. Indeed, in terms of the future of the consortium and research into biodegradable plastics, it is evident that success will hinge on developing a product which can compete on price with current plastics for a large market. The market will be guaranteed if attitudes to the issue of the environmental benefits of substituting renewable inputs for non-degradable ones. At this stage it is unlikely that the government will support the move to bio-based polymer production on a large-scale. The likelihood of production of degradable polymers in South Africa seems low, moreover, due to the fact that big players can't keep up with demand for traditional polymers. Big players are furthermore keen to stimulate a strong recycling industry rather than replacement (FRIDGE, www.nedlac.co.za). Polymer compound research will continue, as the major knowledge benefit is in advanced polymer compound technology, and the opportunity for students to be involved in cutting edge research in the field and publishing in scientific journals. The parameters and objectives may, however, be reworked as new ideas are assimilated and modifications and adaptations dictate. Competition from another source is not of paramount concern at this stage.

In sum, the plastics-from-starch project highlights a number of important things that need to be born in mind in the interest of advancing industrial development and science and technology in the country. Firstly, it is evident that the capacity for technological learning and innovation in research institutions in the country is high. The project depended on an advanced set of capabilities amongst the participating institutions and organisations. Such a skills base and the ability to internalise and advance know-how were critical in migrating ideas and technological processes generated and perfected in Europe to South Africa. Technological adaptation, learning by doing and close interaction between participants underscored the R&D process. This was necessitated by the fact the South African study used a different type of feedstock in the plastic production process and the choice of compounds used in the experiments involving nanoclays composites (hydrotalcite, which is anionic), which presented significant chemical challenges that had to be overcome relatively early on. Furthermore, the South African team were also looking to produce a plastic that incorporated no synthetic polymer compound in its manufacture.

Secondly, financial support from the incentivised government funding programme, THRIP, was critical for commencing with the innovation process. The researchers approached various organisations locally and internationally in order to secure funding. However, it was only after THRIP agreed to fund a portion of the project that the consortium was officially established and research commenced. While internal funds will be used to cover project costs once THRIP comes to an end, this is only an interim measure and securing future R&D funding to advance research in the area is a core priority of the research group.

Thirdly, networking and partnerships were instrumental in driving the project and providing the resources and expertise needed to facilitate technological learning. The European success of R&D and commercialisation of biodegradable plastics has been underpinned by collaborative undertakings and close involvement of numerous public and private institutions and individuals. Given the range of skills and expertise needed in such a research endeavour (materials science, chemistry, metallurgy, plastics manufacture), R&D in biodegradable plastics is seldom undertaken in isolation. Research networks in Europe comprise government ministries, donor organisations, universities, research institutes, and private industries. Furthermore, most of the leading manufacturing companies involved in polymer manufacturing around the world have a diversified product and expertise base and have strong links with partner universities. In South Africa, the project depended not only on the skills and expertise within the three core participants, but also on their linkages with other individuals and organisations providing funding, technological insight, market opportunities and material inputs. Although great advancements were made, no intellectual property was claimed or shared between the participants.

Lastly, the project also highlights the importance of local demand in the R&D and product commercialisation process. In Western Europe, although the cost of manufacturing biodegradable plastics is acknowledged to be greater than that for conventional plastics, the associated environmental benefits of a suitable biodegradable alternative outweigh the costs. Moreover, it is seen as an opportunity to move away from a non-renewal input to a more renewable one. Such a drive is widespread and supported by both private and public sector officials and leading retailers throughout the continent. Consequently, such a high level of demand has resulted in significant R&D and product development efforts. By contrast, in South Africa, demand is reserved to a few select parties interested in the commercial applications rather than the environmental benefits of starch-based biodegradable plastics. Cost is seen as a major deterrent to the widespread replacement of conventional petroleum-based polymer bags. In addition, it was discovered that using starch for the production of plastics also caused accelerated wear and tear of the machinery, thus increasing depreciation costs and the overall cost of production. This cost would have to be passed on the consumer, making the plastics more expensive than conventional plastics. Therefore, until demand shifts from an economic to environmental focus, the parameters of the project will always be narrow in scope and concentrated on the production of niche products such as golf tees, flavoured dog bones, specialised packaging, seedling tubes and pots. A major drive would have to come from the government for a change in legislation in favour of biodegradable plastics, as well as increased government funding for R&D. This will allow suppliers of starch like African Products to have increased demand and push the prices of biodegradable plastics down, making them more competitive against conventional plastics.

4 Conclusion

This paper presented the results of a qualitative review of a collaborative project undertaken between 2002 and 2004 to manufacture biodegradable plastics from maize starch. The case study provides the opportunity from which to explore the micro-dynamics of the innovation process in South Africa and the manner in which firm capabilities evolve and develop over time. In particular, it showed how different, independent research agendas and quests for new opportunities amongst individuals undertaken over a long time combined through mutual interaction and collaboration. It demonstrated how expertise and resources were effectively pooled and brought together from various sources to establish a research environment conducive to innovation and learning and how technological processes and techniques used elsewhere were able to be modified and adapted locally. It also highlighted that although at the end of the funding programme a product had not yet been commercialised, significant advances had been made in developing products suitable for future commercialisation, most notably biodegradable compounds for seedling trays and golf tees. The commercialisation of moulding compounds is envisaged for 2006. A number of intangible benefits also resulted, specifically a broadening of advanced capacities through knowledge transfer and learning by doing. The case study also revealed the importance of private and public sector funding in the R&D process and the challenges associated with matching the unpredictable nature of the research process with established parameters and timeframes. From a government perspective, such insight is needed in order to understand the strengths and weaknesses of the prevailing innovation system and the challenges involved in going forward with national strategies aimed at advancing science and technology and manufacturing in the country.

Acknowledgement

Appreciation is expressed to the Centre for Polymer Technology, CSIR and the Institute for Applied Materials, University of Pretoria as well as to African Products for providing valuable insight into the project.

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Cleaning pollution: from mining to environmental remediation

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February 2006

Chapter 4: Cleaning pollution: from mining to environmental remediation

Abstract

This paper examines the importance of the mining sector in Peru, highlighting the key role it has played through history and plays at present, primarily because of the most favorable geological characteristics of the country, but also noting that it has not led to widespread improvements in living conditions. It then examines the main features of bioleaching as a cost-effective alternative to the conventional methods for processing ores, and describes the initial efforts made during the 1970s to acquire technological capabilities in this field and how these capabilities have evolved over time, placing emphasis on the absorptive capacity of mining firms operating in Peru. The Tamboraque project, run by Minera Lizandro Proaño S.A. (MLPSA), is used as a case study to show the way in which these capabilities were acquired, and partially lost, before indicating how some elements of technological capabilities remained dormant and were displaced to other organizations. Even with these constraints, a process of 'lateral migration' of these technological capabilities took place, which later reemerged in the field of bio-remediation technology. However, the paper also indicates the incipient state of the Peruvian mining innovation system did not facilitate either the consolidation of bioleaching capabilities in the country, nor facilitated this process of lateral migration that took place largely through individual efforts. This suggests that there are opportunities to expand the role of public policies to strengthen the mining innovation system, to consolidate technological capabilities and to expand these capabilities to other sectors and uses.

Acronyms

APGEP	Ambiente, Participación y Gestión Privada (Environment, Participation and Private Sector Management - Program run by USAID)
ASARCO	American Smelting and Refining Company, acquired by Grupo Mexico
BID	Banco Interamericano de Desarrollo (Inter-American Development Bank)
BIOX	Biological Oxidation
GRADE	Grupo de Análisis para el Desarrollo (Group for the Analysis of Development)
CENTROMIN	Empresa Minera del Centro del Perú
CEPAL	Comisión Económica para América Latina y el Caribe (Economic Commission for Latin America and the Caribbean)
CIUU	Certificación Industrial Internacional Uniforme (International Standard Industrial Classification)
CMI	Chr. Michelsens Institutt
COCHILCO	Comisión Chilena de Cobre (Chilean Copper Commission)
CONAM	Consejo Nacional del Ambiente (National Environmental Council)
Cu	Copper
D.L.	Decreto Ley (Law Decree)
DPRU	Development Policy Research Unit
D.S.	Decreto Supremo (Supreme Decree)
EF	Economía y Finanzas (Economic and Finances)
EM	Energía y Minas (Energy and Mines)
EW	Electrowinning
GDP	Gross Domestic Product
GTZ	German Technical Cooperation
HSRC	Human Sciences Research Council
IIWW	II World War
IDRC	International Development Research Centre
INCITEMI	Instituto Científico y Tecnológico Minero del Perú (Scientific and Technologic Mining Institute of Peru)
INGEMMET	Instituto Nacional de Geología, Minería y Metalurgia (National Institute of Geology, Mining and Metallurgy)
MEM	Ministerio de Energía y Minas (Ministry of Energy and Mines)

MLPSA	Minera Lizandro Proaño S.A.
MT	Metric tonne
R&D	Research and Development
S.A.	Sociedad Anónima (Incorporated Company)
SENREM	Sustainable Environment Natural Resources Management
SMP	Sociedad Minera Pudahuel (Pudahuel Mining Society)
SNMPE	Sociedad Nacional de Minería, Petróleo y Energía (National Mining, Petroleum and Energy Society)
SX	Solvent extraction
UNDP	United Nations Development Programme
US	United States
USAID	United States Agency for International Development
VAT	Value-Added Tax

1 Introduction

The mining sector has always been and still is important in Peru. Almost every government since the Republican era, has highlighted the significance of mining and have declared it as the engine of Peru's economic growth. Mining contributes with much of the needed foreign earnings, taxes and employment.

However, the advantages of mining seem to vanish in the longer term. There have been periods, such as the late 1970s and 1980s, in which mismanagement of fiscal rents have promoted macroeconomic imbalances that contributed to generate Dutch disease. At present, fiscal discipline is a sine qua non condition, however, even when mining revenues have more than tripled in the last 5 years, local communities that host mining operations complain bitterly about the negative effects of this activity. For them mining has only meant pollution and more poverty and are taking action to prevent the development of new mining projects.

This situation is not exclusive of Peru, but of almost all developing countries rich in mining endowments. Multilateral organisations are recommending these countries to follow a strategy of adding knowledge in resource-intensive industries (De Ferranti et al., 2002). But besides general prescriptions on human capital formation, good institutions and openness; the question is what kind of knowledge and how it is added to these industries. As opposed to previous efforts to answer these questions that focused on macro or meso analyses, it seems important to review firms' experiences that sustained learning processes and contributed to produce innovations in resource-intensive industries.

This paper consists of ten sections. Section 2 describes the methodology followed for the preparation of this case study. The third section provides an overview of the economic importance of mining in Peruvian economy since the late XIX century to the current years. The fourth section describes the geological characteristics of the Peruvian mining deposits and shed some lights over the division of labour between foreign and domestic mining firms. In the fifth section, the bioleaching technology is described as a cost-effective alternative to the conventional beneficiation method. In addition, it is portrayed the initial efforts made in Peru to acquire technological capabilities in bioleaching, as well as the state of this technology in Peruvian mining. The sixth section analyses the absorptive capacity in Peruvian mining. A brief discussion about this concept is provided and it is complemented with a brief long-run assessment of the technological capabilities of Peruvian mining firms. The seventh section presents the Tamboraque project as the case study that serves to analyse the lateral migration from the bioleaching technology to process complex mineral to bio-remediation technology. The section provides a technical background on the project and analyses the absorptive capacity gained by the mining firm that run the Tamboraque project. The eighth section describes the process by which the research efforts in bioleaching end up in efforts to develop a bio-remediation technology. The ninth section discusses the limited action of the Peruvian mining innovation system in the accumulation and expansion of bioleaching capabilities. The final section provides some comments about the relevance of this case study as an example of lateral migration and about the opportunities present in the current Peruvian context for continuing research efforts in bio-remediation.

2 Methodology

The present case forms part of a set of studies aimed at cumulating evidence about the pertinence and utility of the proposed concept of "lateral migration", meaning the migration of knowledge cumulated in a resource intensive sector to a different one.

As opposed to previous efforts on identifying spillovers, transfer or diffusion of technologies to other sector, this proposed concept focused at the microeconomic level and tried to identify specific technological trajectories. In that sense, the proposed concept is building up in the literature of absorptive capacity and learning, the role of foreign technology in indigenous technological development and linkages and interactions (Lorentzen, 2005).

Interviews with different firms, government and academic institutions representatives were the main methodological tool. The interviews were performed through years because the authors analysed this case study as an example of how linkages between small mining firms, providers and other institutions are generated (Kuramoto, 2001b) and as an example of the influence of mining firms in the mobilisation of public participation in environmental monitoring (Kuramoto, 2002). A last set of interviews was performed in 2005 to gather information for this case study.

In addition to the interviews, various guided visits to the Tamboraque plant were made at the different periods.

3 Economic importance of mining in Peru

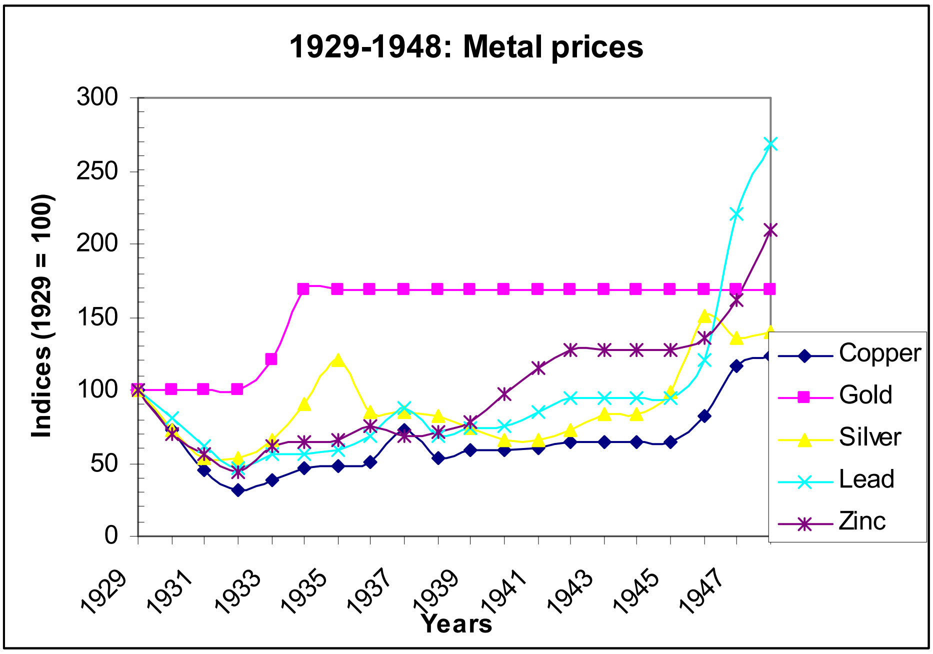
Peru is a country with a large mineral tradition. Since the pre-Colombian era, ancient Peruvians had expertise in the metallurgy of gold and silver, and to lesser extent of copper. The ornamental metallic objects found in many pre-hispanic tombs all over the country are proof of this expertise.

With the arrival of the Spaniards, mining became a widespread economic activity. The focus was on the exploitation of precious metals, such as silver and gold, which were sent to Europe. Thousands of Indians worked at the mining operations and the latest technology of that time was transferred to the sites.

With the independence, mining operations were administrated by domestic entrepreneurs. Changes in markets opened the opportunity to exploit base metals by the end of the XIX century, together with the continuing exploitation of precious metals (Thorp and Bertram, 1975). The modern era of mining began at the turn of the century. Operations became capital intensive, which required skilled labour and engineering capacities. As a result, institutions such as the School of Mines were founded in 1876.

Since then, mining has been one of the leading economic sectors in Peru. Even when price metals instability was a common feature, Peruvian mining succeeded to bypass the revenue imbalances because of the wide variety of metals produced (see figure 10). For example, during the 1929 Depression copper prices went down severely but precious metals soared because of their use as depositary of value. By the 1940s, the rise in price of lead and zinc offset the prior decline of copper. These offsetting effects together with deflationary policies were able to maintain the balance of payments in equilibrium[32] (Thorp and Bertram, 1975).

Figure 10 - Metal prices



Source: Thorp and Bertram (1975)

In the 1940s, an imports substituting model was launched. A set of policies aimed at stimulating internal demand and to capture surplus from the export sectors (via the increase of the tax burden from 4% to 14% in 1945) were put in place. However, some specific measures to support mining were also implemented, such as the creation of the Mining Development Bank to provide credit to local mining firms, at the same time that the IIWW increased the demand for raw materials produced by Peru, especially of metals such as copper, vanadium and molybdenum.

The increasing control of United States interests in the Peruvian economy resulted in Peru's acceptance of wartime prices controls that reduced considerably export earnings. At the same time, the import-substituting policies aimed at expanding the government payroll, adopting full exchange control in mid-1946 and raising wages did not add up to a coherent development strategy. By 1948, it was clear that the model did not work and the country reversed to economic liberalism (Thorp and Bertram, 1975). One example of this reverse was the enactment of the 1950 Mine Code that promoted foreign direct investment in the sector.

During the 1950s and early 1960s, Peruvian mining experienced a sustained growth based on the set up of large projects by foreign investors. However, investment diminished due to the government pressures to increase the retained value of mining and the expectation of foreign firms to be granted more fiscal incentives (Thorp and Bertram, 1975). The halt on mining investment put at risk the whole strategy of export-led growth, since mining was the only export sector capable of rapid large-scale expansion.

The nationalisation of Peruvian mining occurred in the late 1960s, after the military coup in 1968. The state took the large mining operations, but the inefficiency of state

[32] It is important to measure that other exporting industries such as sugar and cotton in agriculture, and a booming fishing industry, contributed as well with important foreign earnings.

firms in conjunction with the collapse of the fishing sector and the increasing imports demand resulted in major problems of balance of payments (Thorp and Bertram, 1975). This situation continued during the 1980s, in which foreign borrowing aggravated the balance of payments imbalances. The result was a major macroeconomic crisis, characterised by monetary instability, distortion of relative prices and recession, which lasted more than a decade and reached a peak in 1988 (Paredes and Sachs, 1991).

During the crisis years (1975-1990), mining investment declined. The only large project launched during that period was Tintaya, a government effort to maintain the sector's dynamism. Macroeconomic imbalances, specifically the appreciation of the exchange rate, discourage mining investment from the private sector. Medium and small mining operations continued operating but became obsolete and inefficient.

Since the 1990s, Peruvian mining is experiencing a resurge after a decade of inertial growth. Changes in legislation that promoted private and foreign investment were accompanied by fiscal incentives and good quality geological information. In fact, the 2001-2002 Survey of Mining Companies elaborated by the Fraser Institute ranked Peru as the 8th country with the highest investment attractiveness index[33], after mining locations such as Alaska and Nevada in the United States (7th and 6th respectively), Brazil (5th), Chile (4th), Australia (3rd) and Ontario and Quebec in Canada (2nd and 1st respectively). In addition, total investment for the period 1996-2000 reached US$ 3.5 billions (MEM, 2005).

Table 8 - 2005: Peru's ranking as world metal producer

Metal	World rank	% of world production
Copper	3	6.89
Gold	6	6.96
Lead	4	9.52
Silver	2	14.35
Zinc	3	15.38

Source: Sociedad Nacional de Minería, Petróleo y Energía (2005)

As shown in Table 8, Peru is ranked as a major world producer in several base and precious metals. Strong positions are held in silver and zinc, in which the shares of world production surpass 10%. In gold, Peruvian operations are known as having one of the lowest operating costs.

With regards to the economic impact of Peruvian mining, this activity has been an important engine of growth since the 1990s. In the last decade, the Peruvian economy has grown at 4% annually, while mining growth rates have increased almost 10%. Thus, the participation of this sector in GDP has augmented from a traditionally 3.5% to 5.8%.

This significant growth in GDP has pushed an important increase in mining exports. These passed from US$ 1,197 million in 1994 to US$ 4,573 in 2003, which represented an increase of 132%. As a result, mining exports share in total exports in 2004, represented 54.8% amounting more than US$ 6.8 billion.

Mining is a capital and technology intensive sector, thus it does not create a large number of jobs. Mining has generated between 3% and 5% of domestic employment. This means around 80,000 direct jobs and 320,000 indirect ones. Based on these

[33] The Investment Attractiveness Index is a composite index constructed "by combining the mineral potential index, which rates regions based on geological attractiveness, and the policy potential index, a composite index that measures the effects of government policy on attitudes towards exploration investment" (The Fraser Institute, 2002).

estimates and considering 5-member families, around 1,600,000 people depend on mining.

Mining is the most important corporate tax payer (at a 3-digit SIC level) in Peru. The corporate tax rate is 30% for all industries. In 2003, it contributed with 23.1% of all corporate tax revenues, while manufacturing contributed with 17% and commerce with 13%.

These figures show that mining is in an expansion cycle, just as 50 years ago when the 1950 Mining Code was enacted. Peruvian economy is again ruled by an export-led growth model based not only on mining but fishing and agro-industrial products. Investment has increased in the last decade. There is macroeconomic stability: low inflation rates, equilibrium in the balance of payments, controlled fiscal accounts, among others. However, the lack of a development vision for the country is a major constraint. Peru is not making advances in knowledge investment and major changes in commodities prices may affect growth rates.

4 Geological characteristics of Peruvian deposits

Mining deposits are found almost in every region in Peru. However, there are regions that are known by their mineral richness and where most mining operations are located. Figure 11 shows the location of the different mining (metallic and non-metallic) operations and it is clearly visible that most of the operations are located along the Andes chain.

Considering the main metallic deposits, it is possible to identify six mining regions (see table 9). The first region is formed by the departments of Cajamarca and La Libertad in the northern part of Peru. This region is rich in gold, copper and complex ores deposits. Yanacocha (operated by Newmont[34] and Buenaventura Mines[35]), the largest gold disseminated deposit is located in Cajamarca, as well as the district of Pataz (La Libertad) where a large number of artisanal miners exploit gold.

Table 9 - Mining regions and type of metallic deposits

Mining region	Type of deposits
Cajamarca and La Libertad	Gold, copper, complex ores (zinc, lead and copper
Ancash and Huánuco	Gold, copper, zinc, complex ores, non metallic
Lima, Pasco and Junín	Complex ores
Huancavelica, Ayacucho and Apurímac	Silver and copper
Ica, Moquegua and Tacna	Copper and iron
Arequipa, Puno, Cuzco and Madre de Dios	Copper, iron and gold

Source: Elaborated by the authors.

The second region is formed by Ancash and Huánuco. This is a region with large gold, copper and zinc resources. Antamina (operated by BHP Billiton[36]), the largest mine of copper and zinc in the world, is located in this region. There are also major

[34] The US firm Newmont is the world largest gold producer.

[35] Buenaventura is the largest domestic mining group in Peru.

[36] BHP Billiton, an Australian conglomerate, is one of the largest diversified mining groups in the world.

gold deposits as Pierina (operated by Barrick[37]) and small operations exploiting rich complex ores.

Lima, Pasco and Junín form the third region, which is characterised by massive small to medium complex ore deposits[38]. Most of the small and medium-size mining operations are located here and were developed in the beginning of the XX century, thus becoming the most important mining region during most of that century. Doe Run[39] operates a major multi-metal smelting plant (La Oroya) which processes the poly-metallic ores that come from the different small and medium-size operations located in the region[40].

The fourth region is formed by Huancavelica, Ayacucho and Apúrimac. This region is rich in medium silver deposits, mostly operated by medium firms. The major copper deposit Las Bambas (Xstrata[41] is currently in the exploration phase) is located in this region. This deposit may become the largest copper deposit in Peru.

Ica, Moquegua and Tacna form the fifth region. Ica is known by its large iron deposit of Marcona (operated by Shougang[42]) and its small gold deposits that are exploited by artisanal miners.

Moquegua and Tacna are known by their large copper deposits of Cuajone and Toquepala (operated by Southern Peru[43]) and Quellaveco (currently in exploration by Anglo American[44]).

Finally, the sixth region is formed by the departments of Arequipa, Puno, Cuzco and Madre de Dios, which are located in the Southern part of Peru. There are two major copper operations in Arequipa and Cuzco: Cerro Verde (operated by Phelps Dodge[45]) and Tintaya (operated by BHP Billiton), respectively. Puno has the San Rafael tin deposit, which is responsible for all the domestic tin production, as well as small gold deposits that are exploited by artisanal miners. Madre de Dios has alluvial gold deposits that are exploited by artisanal and informal miners.

The six mining regions have different types of deposits that attract different kinds of mining entrepreneurs. On the one hand, large mono-metallic deposits that usually are exploited by foreign firms or by joint-ventures and, on the other hand, small and medium deposits, usually with complex ores, that are exploited by domestic mining

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[37] Barrick, a major Canadian firm, is a leading international gold mining company, with a portfolio of operating mines and development projects located in the United States, Canada, Australia, Peru, Chile, Argentina and Tanzania.

[38] The Tamboraque mine, which is the subject of study of this paper, is located in the department of Lima, province of Huarochirí, district of San Mateo de Huanchor.

[39] The Doe Run Company is a US leading provider of premium lead and associated metals and services.

[40] La Oroya is the metallurgical complex constructed and owned by the US Cerro de Pasco Corporation. This complex was constructed by the beginning of the XX century and became the heart of the Peruvian mining industry for several decades. The assets of Cerro de Pasco Corp. were expropriated in the late 1960s during the nationalization process held in Peru.

[41] Xstrata is a Swiss diversified mining group. It operates in six major international commodity markets: copper, coking coal, thermal coal, ferrochrome, vanadium and zinc, with additional exposures to gold, lead and silver.

[42] Shougang is a major Chinese steel manufacturer.

[43] Southern Peru Copper Corporation operates in Peru since the 1960s. It was owned by the US firms ASARCO and Phelps Dodge. At present, it is owned by the Grupo Mexico.

[44] Anglo American is a South African leader in mining and natural resources. It owns a well diversified range of high quality assets covering gold, platinum, diamonds, coal, ferrous and base metals, and industrial minerals.

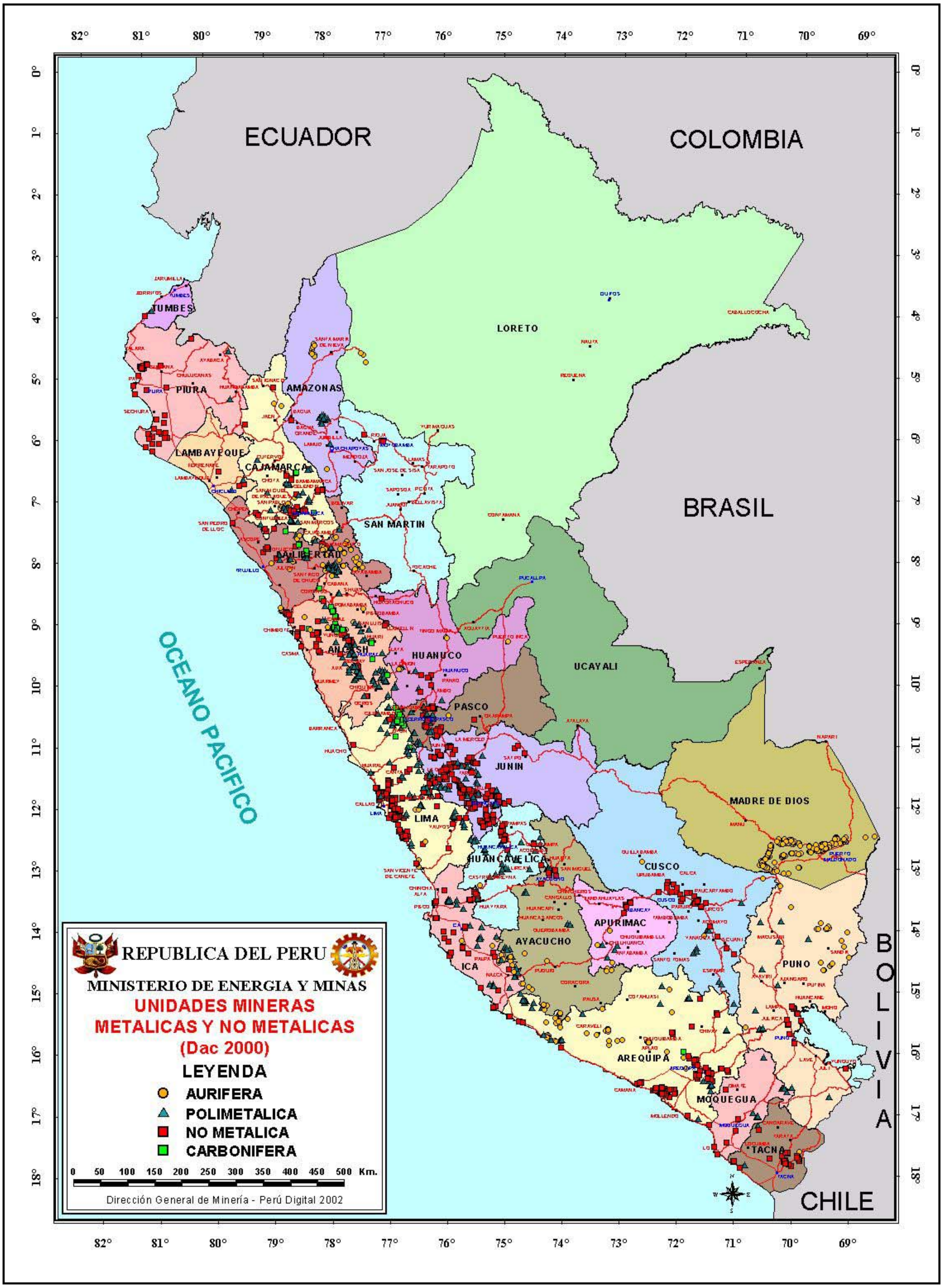
45 Phelps Dodge Corp. is a US firm and one of the world's leading producers of copper. The company is a world leader in the production of molybdenum, the largest producer of molybdenum-based chemicals and continuous-cast copper rod, and among the leading producers of magnet wire and carbon black.

groups. In addition, there are very small gold deposits that attract artisanal and informal miners.

The latter division of labour has major technological implications since large mining international groups are interested in large mono-metallic deposits that can be exploited by standard technology that is procured by international sources. In contrast, small complex and rich ores are exploited by domestic groups. Though the technology to process these complex ores is the standard flotation technology46, their specificity requires an intense adaptation of the technology resulting in the set up of different flotation circuits to extract the different metals contained in this kind of ores. Alternative routes to process these ores, such as pressure leaching, are being essayed in places like South Africa and Australia, but their application still remains risky.

[46] In the flotation stage, water and reagents are added to the milled mineral. Air is blow to the solution till bubbles are formed. Metal particles adhere to the bubbles and other material goes to the bottom of the flotation cells. Then metal is collected from the bubbles and dry by ventilators. This process is repeated in every flotation circuit to collect different metals.

Figure 11 - Metallic and non-metallic operations in Peru

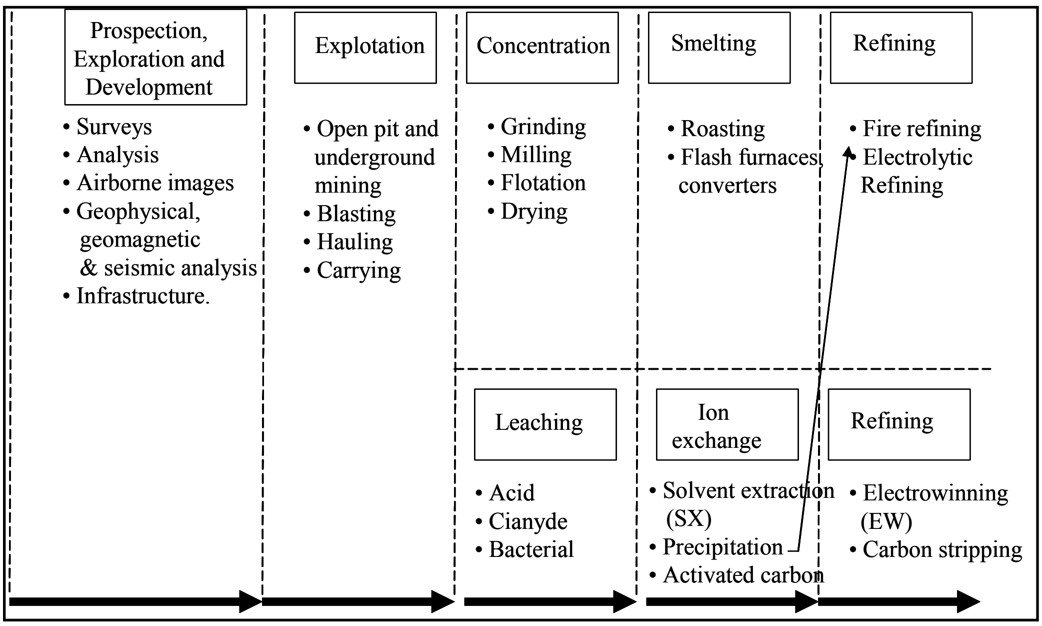


5 Bioleaching in the Peruvian mining sector

5.1 Hydrometallurgy: a radical innovation in metallurgy

The typical stages in metal production are prospecting and exploration of deposits; mining; and metal recovery from mined ores (see figure 12). In the first stage, mineral deposits are identified and analysed to figure out the richness of the deposit measured in terms of percentage of metal content and the total tonnage of ore. If the exploration studies proof successful, development and infrastructure works begin to secure access to the resources and their transportation to major ports for their export. The mining stage involves all the tasks to extract the mineral from the deposit, including the preparation of the mine, its exploitation and the hauling of the mined ore to the processing site. Finally, three stages are required for metal recovery. Concentration involves the crushing and milling of mineral, as well as the use of the flotation technology to extract the value metals from the milled material. The resultant output is a concentrate of metal which has around 30% to 40% purity. Because of the complexity of ores, a concentration plant is formed by several flotation circuits to extract different metals. Thus, there must be some adaptation (order of extraction of different metals, selection and amount of different reagents, etc.) to treat specific metals. In the stage of smelting, the concentrate is exposed to high temperatures in furnaces. This exposure provokes chemical reactions that allow the production of bars of metals with around 98% purity. The final stage of refining, the bars are further exposed to furnaces to increase their purity to 99.99% or, are exposed to reagents and electricity that generates ion exchange and an increase in purity of 99.99% or more.

Figure 12 - Stages of mining process



Source: Elaborated by the authors.

By the late 1960s, an alternative route to produce metals, especially copper, was available. It did not involve a complete change in the process but an alternative route after the mining stage. Once the mineral is extracted, the main stages of this method are leaching and precipitation to continue processing the mineral by pyrometallurgy or, alternatively, leaching, solvent extraction and electrowinning[47].

The leaching stage is crucial in this method. In general, copper ores or mine wastes are sprayed with an acid solution that dissolves iron from the mineral and allows copper to be liberated. There are two main leaching alternatives. Acid leaching, in which sulphuric acid or ammonia is sprayed over the mineral ore, is mainly used to treat oxide minerals coming from dumps that contain as low as 0.2% of copper per metric tonne (MT). This low-content material is too expensive to be treated by the conventional or pyrometallurgical method. Bacterial leaching, on the other hand, is used to treat sulphide ores or concentrates. It is widely used in Chilean operations, where all large mining operations have a hydrometallurgical plant and the electrowon cathodes represented 31% of all the copper produced in 2004 (Valenzuela y Arias, 2005). However, the use of bacterial leaching, as opposed to acidic leaching, to treat concentrates is not widely spread, although different firms claimed to have developed technologies that can be applied in commercial operations.

The leaching solution – i.e. acid and/or bacterial – is sprayed over the mineral which is accommodated in heaps. The solution percolates and the resultant liquid – i.e. pregnant solution – is collected for further treatment. Optimisation of leaching depends on the time and speed of spraying the solution and on the accommodation of the mineral to allow a chemical reaction to occur in the shortest time possible and with the highest copper recuperation. The pregnant solution can be precipitated through a pile of scrap iron or steel and the copper precipitates to the steel surfaces. A chemical reaction occurs: there is a transfer of electrons between the iron and the copper. The output is called cement copper and contains about 85% to 90% of copper. Cement copper must subsequently be treated through smelting and refining. Copper cementation was the typical way to recover copper from the pregnant solution.

An alternative route is solvent extraction and electrowinning (SX-EW). The development of solvent extraction contributed to make economically feasible the hydrometallurgical method[48.] The development of powerful reagents was crucial to achieve high metal recovery rates (Tilton and Landsberg, 1997). The pregnant solution is pumped to tanks where it is mixed with an organic chemical – i.e. reagent – which dissolves copper. The copper-laden organic solution is separated from the leachate – i.e. residual from the pregnant solution – in a settling tank. Sulphuric acid is added to the pregnant organic mixture and the acid strips the copper into an electrolytic solution. This process is performed in closed loops. Thus, both the leachate and the organic reagent are used again to treat more copper.

Finally, the rich electrolyte that results from the solvent extraction stage is sent to the electrowinning circuit that accommodates stainless steel cathodes and lead alloyed anodes. An electric current is run through the electrolyte and the copper is settled onto the cathode. The output is also 99.99+% copper cathodes. The remaining depleted electrolyte is sent back to the solvent extraction circuit and/or the leaching solution tank to start again with the process.

Hydrometallurgy became the basis of the US copper industry since it allowed a reduction in production costs and the use of marginal ores that were considered as

[47] There are some deposits that are being exploited from the beginning of the 20th century by the hydrometallurgical method – i.e. in-situ leaching. Those deposits contained in permeable rock are injected with a leaching solution, thus eliminating the stage of mining.
[48] Solvent extraction was first developed in the 1940s to produce uranium.

waste (Tilton and Landsberg, 1997; O hUallacháin, B. and R. Matthews 1996). First, the hydrometallurgical method had lower costs than the conventional method. By 1996, costs estimates for US copper operations were US$ 0.69 for the conventional method against US$ 0.39 for hydrometallurgy (Pincock, Allen, and Holt, 1996). Most of this savings come from lower costs in the stages of mining and milling. Second, hydrometallurgy cost effectiveness is not subject to economies of scale. Pincock, Allen and Holt (1996) showed that different estimates indicated that the efficient size for leaching, solvent extraction and electrowinning operations is reached at capacities of 15,000 Cu metric tonne (MT)/per year, while the conventional method requires minimum capacities of 50,000 Cu MT/per year. Third, the lower capital investment requirements for the hydrometallurgical method represented a great incentive. Pincock, Allen, and Holt (1996) estimated that the capital needs to construct a SX-EW plant averages about US$ 3,400 per annual tonne of cathode capacity and that expansions of existing facilities average US$ 1,700 per tonne. In contrast, the resources required to produce a copper tonne in the conventional route ranged between US$ 8,000 and US$ 10,000 as shown by Domic (2002).

The advantages of the hydrometallurgical method had limits. Before the development of bacterial leaching, it was not cost-efficient to treat sulphide ores, which conform a large share of world copper reserves. In addition, the large pyrometallurgy capacity around the world becomes a major constraint to set up more hydrometallurgy operations, since smelters and refineries need to be fed by concentrates to continue in operations. Nevertheless, the share of primary copper produced by hydrometallurgical operations has increased steadily since the late eighties. By 1987, electrowon copper (the final product of the hydrometallurgical method) represented less than 10% of total primary copper output, while its share increased to 20% in 2002 (Kendrew, 2003).

5.2 Bioleaching efforts in Peru

The advantages of hydrometallurgy were soon acknowledged by other mineral producing countries. On the one hand, developing countries that initiated a process of nationalisation of their mines and deposits saw in this new method a way to decrease their dependence on foreign technology and to reduce the capital investment required to set up a new mining operation. On the other hand, these countries foresaw that the development of bioleaching, the use of bacteria to speed up the leaching of sulphure and complex ores, was at its early stage. Thus, it was a good opportunity to absorb and build capacity in bioleaching and hydrometallurgy. In addition, a window of opportunity was open since industrialised countries, such as the US, were only interested on acidic leaching since there was a great availability of oxidised dumps and will not make major efforts to investigate the action of bacteria in sulphur ores (Warhurst, 1985). Also, industrialised countries owned most of the smelting and refining capacity and were interested in engaging in long-term purchase contracts of concentrates.

Within this context, the Andean Pact launched two projects to investigate and apply bacterial leaching to recover copper in the late 1970s. The projects “Acid or bacterial heap and dump leaching for marginal copper ores” and “Copper recovery from ion exchange in copper sulphate solutions” were aimed at developing hydrometallurgy (PADT-Cu) in Peru and Bolivia.

The specific objectives of these projects were to develop appropriate technology to exploit domestic mineral resources with biological sources available in the region; to develop semi-industrial facilities to support the diffusion of this technology; to implement bacterial leaching operations using complex mineral dumps and/or abandoned sulphur copper deposits; and to promote the increase of copper production via this new technology (Macha and Sotillo, 1975).

To conduct the activities of these projects, CENTROMIN[49] set up a laboratory in La Oroya and pilot dumps were built in Toromocho (Morococha). In addition, MINERO Peru and INCITEMI[50] set up research centres in Arequipa and Lima. In parallel, the activities of these projects served to test the commercial application of this technology. A pilot solvent extraction and electrowinning (SX-EW) plant was built in Cerro Verde (Arequipa), which later became the fourth commercial plant in the world that deployed this new technology[51].

The set up of Cerro Verde was a major technological success for Peruvian mining since it was the first large project developed entirely by a Peruvian state-owned company and, furthermore, it deployed a non conventional technology. As opposed to US hydrometallurgy operations that processed material cumulated in dumps, Cerro Verde was a complex operation. It was designed to exploit first the superficial layer of copper oxides by acidic leaching (using sulphuric acid) and in a second stage exploit the sulphures by the conventional method. In this way, the sell of copper cathodes from oxide ores would finance the setting up of the large concentration plant[52.] However, government budget constraints and the emerging macroeconomic imbalances impeded to continue with the second stage of the project. As a result, Cerro Verde began experimenting with the addition of bacteria to the leaching solution to accelerate the liberation of copper from the sulphur ores. Bacteria is found naturally in acid mine water. Thus, the research required the identification and selection of bacteria and the addition of the appropriate strains in the leaching solution. It also required experimentation in the mineral heap (height, degree of compacting of the ore, etc.).

Being a state-owned mining firm, Cerro Verde became an experimenting site because its shrinking investment budget forced the firm to find technological solutions at home. For example, due to the increasing costs of lead anodes used in the electrowinning phase, the firm managed to get a donation from the Japanese government to set up an anode plant in Cerro Verde[53].

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[49] CENTROMIN PERU was the state-owned mining firm that operated the previously owned facilities of Cerro de Pasco Corp. EXPLAIN

[50] MINERO PERU was the state-owned mining firm aimed at developing new mineral deposits, such as Cerro Verde, where part of the research activity was conducted. INCITEMI was the National Mining Research Institute; it later became the INGEMMET (Instituto Nacional de Geología, Minería y Metalurgia).

[51] The first comercial SX-EW plant in the world was Blue Bird constructed in the United States in 1968. It was followed by Bagdad (1970), also in the United States; Nchanga (1973) in Zambia; and Cerro Verde (1974) in Arequipa, Peru.

[52] Lack of international funding sources was a common constraint faced by mining nationalised firms.

[53] Information obtained in an interview with a former President of Cerro Verde.

Table 10 - Promotional mining laws

Date	Law no.	Law title
Aug. 1991	D.L. 662	Promotion of Foreign Direct Investment
Sept. 1991	D.L. 674	Promotion of Private Investment in State-Owned Firms
Nov. 1991	D.L. 708	Promotion of Investment in the Mining Sector
Nov. 1991	D. L. 757	Framework for the Growth of Private Investment
Jun. 1992	DS-014-92-EM	General Law of Mining
Oct. 1992	DS-162-92-EF	Guaranty Regime for the Private Investment
Jun. 1993	DS-024-93-EM	Regulation for the Guaranty and Measures for Promoting Investment
Apr. 1996	D.L. 818	Incentives to the Investment in Natural Resources
Apr. 1996	DS-058-96-EF	Regulation for the Incentives to the Investment in Natural Resources
May 1996	Law 26615	National Mining Cadastre
Nov. 1996	D.L. 868	Modifications to General Law of Mining
Jan. 1998	Law 26911	Anticipated VAT recovery for Natural Resources Exploitation
Mar. 1998	DS-027-98-EF	Tax Incentives for Reinvested Profits
Aug. 1998	DS-084-98-EF	New Regulations for Contracts Signed with the Government in Natural Resources
Sept. 1998	DS-095-98-EF	Loss Carry Forward for Periods Longer than 4 Years

Source: Sanchez (1998)

Despite these technological achievements, the financial situation of Cerro Verde was critical. Due to macroeconomic unbalances during the 1980s, the firm's revenues were controlled directly by the central government and deviated to cover fiscal deficits[54] (Becker, 1983). As a result, there was a deterioration in its productive efficiency and a reduction of further research to improve the SX-EW plant.

The expansion of technological capacities resulting from these experiences was very limited since they were not tightly integrated to the work of universities. Even when at an early stage universities were involved in these projects, further basic research was not done. As a result, there is a limited amount of theses on the topic and universities did not include courses on leaching, or hydrometallurgy, in the curricula of mining and metallurgic engineering and, as a result, did not promote the specialisation of professionals in leaching processes. In addition, the restraint in mining investment limited the possibility of setting up new leaching facilities and of diffusing this technology, such as Toromocho, a mining deposit where some of the experimentation was performed.

This situation represents the opposite of what happened in Chile, where experimentation with bacterial leaching was also essayed. In Chile, early efforts in bacterial leaching were done by the private sector, but soon the engineers commanding the research offered courses at the universities with major mining and geology faculties and engaged students in the research projects. This served to create a minimum critical mass of specialised professionals. In addition, the attractive investment conditions granted to foreign investors converted Chile in one of the few countries in Latin America where new mining operations were developed. Most of the operations opened in the 1980s used bioleaching technologies. At present, Chile continues to promote the study of bacteria and has devoted around US$ 5 million in

[54] This kind of financial interference was common in the nationalized mining firms in the developing world. These firms were revenue maximisers rather than profit maximisers. This explains why during periods of low prices, these firms increased their output instead of reducing it.

the research initiative Genoma Chile, aimed at improving existing and creating new bioleaching technologies[55].

The Peruvian mining as a whole suffered from the macroeconomic imbalances and grew at an inertial rate. It is in the 1990s, with the revitalisation of the international mining industry, that the Peruvian government made major changes in legislation to attract private investment (see Table 10). Different pieces of legislation were enacted to promote private investment, to give positive signals to foreign investors in the form of tax incentives, provisions to make remittances and to carry loss forward, among others. With these changes, a privatisation process began and mining investment increased in Peru.

This increase of mining investment also meant the modernisation of existing operations and the use of new technologies. One of these technologies, although not unfamiliar to Peruvian mining, was bioleaching. It was first introduced in 1994 in Yanacocha, a mine operated by Newmont and the Peruvian Buenaventura. Yanacocha meant the beginning of gold mining at a large scale. Other operations like Pierina, operated by Barrick, followed. A couple of years later this technology was introduced in the large Toquepala operation. Toquepala is a copper mine owned by Southern Peru, the only foreign firm that survived the nationalisation process initiated in the late 1960s in Peru[56].

Interviews with representatives of these firms revealed that none of these projects used any experience accumulated in the Andean Pact project. Some of them did not even heard about this project. In the case of the gold operations, Newmont realised that the geologic structure of Yanacocha was very similar to the gold deposits they exploit in the United States and used their expertise to develop Yanacocha, which became their most profitable mine.

The development of the SX-EW plant at Toquepala, followed the same pattern of other operations in the United States. The mine had been operating for more than 30 years and had accumulated large dumps with low grade material. Thus, Southern Peru commissioned the plant to one international engineering company. The firm's representatives were asked if they made consultations with Cerro Verde engineers but the answer was negative. They mentioned that some visits were made to Chilean operations to see their SX-EW plants.

Cerro Verde's representatives confirmed that they did not receive any inquiry or consultation from Southern Peru. But what is surprising is that representatives from Chilean firms did contact Cerro Verde. From these testimonies, it seemed that the domestic technological capacity in this technology was not acknowledged in the country, but it was valued abroad[57].

The cases mentioned above correspond to large mining operations. For smaller operations it is more difficult to find cases of adoption of new technologies since there is always a financial constraint. Peru does not have a developed capital market. Commercial banks in Peru usually do not finance long-term productive projects, such as the mining ones[58], and before the 1990s, small and medium mining firms did not have access to foreign funding sources. Most of the investment performed in this

[55] See the webpage of the initiative: URL: http://www.genomachile.cl/

[56] Southern Peru survived the nationalization because was able to show the Peruvian government advanced plans to open another large copper mine (Cuajone) in the next 5 years after the expropriation process began (Becker, 1983).

[57] In fact after the privatization, Cerro Verde was acquired by the American Cyprus Amax. This company did maintain most of the technical staff that worked in Cerro Verde and they did not execute drastic changes in the SX-EW plant design or other parts of the operation.

[58] Becker (1983) and Thorp and Bertram (1975) reported the family links of the domestic entrepreneurial mining groups regarding its ties to the financial sector. Some of these groups owned some stake at the commercial banks, thus facilitating their access to funding.

mining strata is done with personal savings or retained profits. This kind of funding limits the growth of these mining operations.

In addition, the legal mining framework does not provide any policy tools to attend the needs of this mining strata. In fact, the Mining Development Bank, a financial institution created to provide funding to small and medium mining projects was closed in the early 1990s[59] and, at present, there are no financial institutions to finance small and medium mining firms in Peru[60]. This lack of funding and technical support for small and medium firms conditions them to deploy traditional mechanised technology. However, during the late 1990s, the domestic firm Minera Lizandro Proaño S.A. (MLPSA)[61] decided to adopt an hydrometallurgical method to extract gold from cumulated dumps in the Tamboraque mine. The venture required an investment of around US$ 28 million and the collaboration of different institutions. As opposed to the previous large mining projects, the Tamboraque project is the only one that rescued personnel who participated in the Andean Pact projects and explore the use of bacterial leaching. In addition, it represented a major technological advance for Peruvian mining since it was developed completely domestically.

Just as in the case of Cerro Verde, the Tamboraque project faced financial difficulties that obliged to accelerate the expansion of the plant at the expense of continuing with technical studies. At the end, the project collapsed because the mine could not produce enough material to feed the plant and the firm failed in repaying loans. This commercial failure had major effects in promoting technological capacity accumulation in Peru. Firms that were following with attention the assimilation and adaptation of technology made by MLPSA got discouraged to imitate the firm. This practically marked a halt in the endogenous development of hydrometallurgic methods for gold leaching in Peru.

Even when firms abandoned their efforts to imitate and adopt similar hydrometallurgic methods, the academic interest of a biologist that worked in the Tamboraque project was crucial to build a team at Universidad Particular Cayetano Heredia that is currently working with bacterial leaching for remediation applications.

6 Absorptive capacity in the Peruvian mining sector

6.1 The conceptual framework

Absorptive capacity refers to firms' ability to recognise, assimilate and exploit external knowledge (Cohen and Levinthal, 1990). This concept considers firms as learning subjects or organisations that are able to increase their knowledge base and thus augment their capabilities. The process is continuous and cumulative, so the more external knowledge a firm absorb, the more it acquires new capabilities (Lane, Koka and Pathak, 2002).

Although the concept has proved to be very useful in different fields of study such as strategic management, technology management, international business and organisational economics; some authors have asked for a more accurate definition (Lane, Koka and Pathak, 2002; Zahra and George, 2002).

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[59] The Mining Development Bank had collapsed since it had a huge amount of unpaid loans and was de-capitalised.
[60] In 2004, the Lima Stock Exchange has created a mechanism to raise funds for small (junior) mining firms, but it is not wide spread.
[61] MLPSA is a domestic mining firm that owns small and medium mines that exploit complex ores in the departments of Lima and Junín. MLPSA was founded by the beginning of the XX century.

After reviewing a set of studies using the absorptive capacity concept, Zahra and George (2002) redefined it as "a set of organisational routines and processes by which firms acquire, assimilate, transform and exploit knowledge to produce a dynamic organisational capability". Their contribution is that they identified the components of each one of the firms' capabilities involved in absorptive capacity, thus helping to identify variables that can grasp the mechanisms involved in the process of acquiring external knowledge and exploiting it to generate value.

Table 11 summarises Zahra and George's proposal. The routines involved in the *acquisition* dimension depend on prior experience, but the efforts that the firm devotes to gather external knowledge shape the quality of a firm's acquisition capabilities. *Assimilation* refers to those routines that help understand the information obtained by external sources; these include interpretation, comprehension and learning. *Transformation* relates to routines that help the firm to combine its existing knowledge and the one that has been assimilated. It requires identifying synergies, re-codifying existing knowledge and associating different bodies of knowledge in a creative way. Finally, *exploitation* refers to routines that allow firms to create new competences or improve previous ones by incorporating acquired and transformed knowledge into its operations.

Table 11 - Dimensions of absorptive capacity

Dimensions / capabilities	Components	Role and importance
Acquisition	Prior investments Prior knowledge Intensity Speed Direction	Scope of search Perceptual schema New connections Speed of learning Quality of learning
Assimilation	Understanding	Interpretation Comprehension Learning
Transformation	Internalisation Conversion	Synergy Recodification Bisociation
Exploitation	Use Implementation	Core competences Harvesting resources

Source: Zahra and George (2002), page 189.

It is important to mention the role that the two different kinds of knowledge have in the acquisition of absorptive capacity. On the one hand, codified knowledge is represented by the firm's familiarity with the specific knowledge that is to be absorbed, as well as the number of interdependent technologies, routines, resources linked to it. Thus, a firm should have a broad knowledge base to effectively absorb external knowledge. On the other, tacit knowledge is represented by the implicit and non-codified skills and know-how. Social interaction in formal and informal settings is crucial to absorb this kind of knowledge.

Nonaka (1994) reports that these kinds of knowledge are complementary. For him, knowledge is converted from tacit to codified through four processes. Socialisation, converts tacit knowledge to another form of tacit knowledge, it happens when people share experiences but also via observation, imitation and practice. Externalisation, converts tacit to codified knowledge, it appears within collective reflection or dialogue, when people conceptualise experiences. Combination is a process of systematising concepts and of knowledge transfer among different groups within the firm. Internalisation is the process of assimilating concepts and transforming them into tacit knowledge.

There are five enablers for knowledge creation within a firm. First, a knowledge vision that becomes the knowledge premise that guides work. Second, a knowledge strategy that defines what kind of knowledge to develop. Third, the firm's structure that conditions the communication flow within the firm. Fourth, the knowledge conversion system that includes all knowledge networks related to the firm, such as competitors, customers, related industries, regional communities and subsidiaries. Finally, the firm's staff, especially middle managers that support, nurture, initiate and complete the knowledge conversion processes (Nonaka, 1994).

One common attempt to measure knowledge empirically is through quantifying R&D expenditures. Even when the purpose of R&D is to create new knowledge, it also helps to build up absorptive capacity. In complex learning environments, where the cost of learning is high, R&D becomes crucial to increase the absorptive capacity of a firm. The same occurs when the technology is complex. Thus, the factors that influence R&D also affect absorptive capacity (Cohen and Levinthal, 1990).

With regards to spillovers, Cohen and Levinthal (1990) have a restricted definition of the knowledge that spills out from a competitor. They state that when the competitor has already benefited from the knowledge she has created, it should not be consider as a valuable knowledge for the firm. However, in a developing country setting where R&D is limited and appropriability is weak, spillovers represent good means to increase absorptive capacity. This, however, does not mean that internal R&D is not important. In fact, in such a setting the typical definition of R&D, as a proportion of sales may not be observable, since firms devote resources to R&D but in an informal way and not through budgets.

6.2 Technological capabilities in the Peruvian mining firms

The Peruvian mining industry has always been articulated in response to external demands, for around 90% of all metal production in Peru is exported. Because of this, the sector responded to the technical requirements of foreign customers and, as a result, it imported the mineral processing technologies that met those requirements and set aside indigenous technologies that might have been effective for metal production as the archaeological findings give evidence.

Thorp and Bertram (1975) report that, as early as 1816, domestic mining entrepreneurs were eager to introduce new technologies, such as steam engines. It is important to mention that the establishment of the School of Mines in 1876 contributed to the training of mining engineers that were crucial to the adaptation of foreign technology to the special needs of Peruvian deposits[62].

A change in this pattern of technological adoption occurred with the entrance of foreign capital to Peruvian mining in 1901. The US firm Cerro de Pasco Corporation built the first large scale mining operation in Peru. Cerro de Pasco made major investments in infrastructure to overcome the drainage problem that had previously limited the growth of mining in the district of Cerro de Pasco[63] and set up the first large smelting in Peru (Thorp and Bertram, 1975). That major investment meant the transference of a complete technology package and the hiring of foreign technical staff. Some Peruvian engineers were hired by Cerro de Pasco, but the charges with the highest responsibility were kept to US engineers. Anyhow, Peruvian engineers

[62] By that time, the Peruvian mining industry was located mainly in the Sierra Central region. Mineral deposits in this region contain usually complex poly-metallic ores (i.e. lead, zinc, silver).

[63] Thorp and Bertram (1975) reported that Cerro de Pasco mines required a drainage tunnel that without the foreign capital inflow would have taken between five and ten years to construct (page 81).

received a good in-house training at the Cerro de Pasco and most of them became mining entrepreneurs or chief engineers in other mining operations[64].

In the 1930s, the increase of silver prices encouraged domestic entrepreneurs to invest in mining in other areas of the country. Later on, the introduction of the flotation technology, which allows the production of readily to commercialise mineral concentrates, and the increase of demand in lead and zinc, which are associated to silver, permitted a resurgence of the domestic industry. In this period, Peruvian mining firms showed great aptitudes to acquire, assimilate, transform and exploit new technologies. As a result, flotation plants diffused very rapidly and were adapted to the different conditions that complex ores require in each mine. Thus, it is usual to find plants with various flotation circuits to extract different metals at a sequential mode.

In addition, institutional factors such as the creation of the Mining Development Bank (Banco Minero) and of the Peruvian Mining Engineers Institute were crucial to support technological diffusion and adaptation in the sector. The latter institute began organising mining conventions that became a socialisation space for mining professionals and entrepreneurs.

The coexistence of foreign and domestic firms has been a constant feature of the mining industry in Peru through the years. Even when changes in regulation have favoured the entrance of foreign capital, domestic mining has remained and was able to absorb technical expertise from foreign firms. In fact, a means for this absorption was through human capital mobility. Most of the engineers in charge of domestic operations had, at one point of their careers, worked for a foreign firm (Kuramoto, 2001).

Socialisation among mining professionals is very strong in Peru. Conventions organised by the Peruvian Mining Engineers Institute, by the National Geology Society and by the Engineers Association, among others; have served to share technical experiences. However, this has not led towards formal cooperation among mining firms (Kuramoto, 2001).

Another important issue that has to be analysed with regards to the absorption capacity in Peruvian mining firms has to do with the technological characteristics of the mining process. Mining has a strong dependence on the exploitation of economies of scale and, therefore, relies heavily in mechanisation. Thus, technological capabilities in mining are concentrated in the mastering of production engineering (Ala-Härkonen, 1997; Pogue, 1998)[65]. Successful mining firms are those that reach high efficiency levels in each of their unit operations through 'learning by doing'. However, since the mining process is very complex, production capabilities are required to minimise bottlenecks among the different stages of the process[66]. Even when the mining process is highly standardised, it is also very location specific, since technologies and processes have to be adapted to specific characteristics of the mineral and the deposit's topography.

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[64] That is the case of Alberto Benavides de La Quintana, Peruvian mining engineer that after graduating worked at Cerro de Pasco and later became the owner of Buenaventura Mines, the most powerful domestic mining group in Peru and co-owner of Minera Yanacocha.

[65] Ala-Härkonen (1997) showed that mining firms diversify within the same mining sector; whether it is horizontally, through the production of other minerals; or vertically, through vertical integration. Successful firms must domain their productive processes, so they can generate synergies that allow them to obtain higher profitability levels. On his side, Pogue (1998) suggested that South African mining firms developed following the model of 'financial houses' that helped secure funding for new mining operations. However, funding was always accompanied by technological and engineering capacities to serve new projects.

[66] Thus, it is crucial that engineering firms design the plant layout. It is also required the existence of engineering capacity within the mining firms to understand the blueprints they commissioned.

One of the major constraints to create new knowledge in Peruvian mining is that knowledge generating institutions remain isolated and have limited interactions with mining firms[67]. On the one hand, the main function of the National Institute of Geology, Mining and Metallurgy (INGEMMET), which was created in 1972 to do scientific and technological research in the fields of geology, mining and metallurgy, at present focus its efforts only to prepare the geological map. Any effort that this institute has made to provide services to mining firms has failed[68]. On the other hand, traditionally universities with mining, metallurgy and geology faculties have as main focus to train engineers and have neglected basic or applied research. As a result, limited mining knowledge creation capabilities are created or accumulated within the mining sector, except for the production capabilities accumulated by mining firms. In addition, universities do not interact with mining firms thus firms do complain that recently graduated engineers have to be trained in-house because their skills do not fit the firms' needs. It is only in recent years that some of the universities are trying to establish relationship with mining firms, but they are still not successful. As a result, there has been limited success in transforming or combining different bodies of knowledge that could lead to major (radical) innovations, especially in the area of metallurgy given the complexity of Peruvian ores.

Firms perform some informal research and development (R&D), but it is mostly focused to optimise their processes; for example, performing minor changes into the mining process to increase the metal recovery rate. Some of these R&D efforts are recorded and presented as technical works in different mining conventions. However, in international events it is clear that Peruvian mining firms have little participation. For example, in the International Conference Copper 2003, the Peruvian firm Cerro Verde presented one technical work in the Hydrometallurgy section, compared to four presented by each Chile and the US, two from each Canada, Finland, Australia and Japan[69] [70].

7 The Tamboraque project

7.1 Introduction

The Tamboraque mining project, owned by the firm Minera Lizandro Proaño S.A. (MLPSA), had unique characteristics. As opposed to the typical project in the small scale mining in Peru, it involved intense technological improvements and a close interaction between different agents.

In this project, a lead and zinc mine was transformed in a gold one through a new technology for the Peruvian mining industry. Tamboraque's mineral is a complex ore with main contents of lead and zinc, and to a lesser extent gold. For most of the 20th century, there was no available technology to recover the gold from this complex ore[71]. MLPSA decided to cumulate tailings (residuals and waste material) into dumps

[67] This isolation is a common feature of systems of innovation in Peru (Mullin Consulting, 2003).

[68] One of the common complaints of mining firms is that the INGEMMET pretends to do basic research when dealing with the actual problems of firms.

[69] See list of technical works at http://depo.zaiko.kyushu-u.ac.jp/~sozai/Copper-Cobre-2003-hydro.html

[70] It is interesting to note that no Peruvian university or mining institute presented a work at this conference.

[71] It is interesting to mention that by the 1950s, Yanacocha was first classified as a copper deposit. It is when the technology of cyanide leaching becomes available that massive disseminated gold deposits (with grades as low as 0.2 ounces of gold per metric tonne of material) can be exploited.

till they find a way to recover the gold. However, by 1998 Tamboraque was able to build a plant that recovered gold through a cyanide-based technology with added bacteria from long cumulated dumps (see).

Figure 13 - Tamboraque BIOX Plant

Source: Goldfields (2001)

The project involved the participation of several actors. This was particularly important for a small family-owned mining firm, which traditionally depends on its own limited technical and financial resources. In this case, the project counted with the participation of two multinational investment funds, Repadre International Corp. y Global Environment Emerging Markets Fund, which provided part of the US$ 23 million required (Minas y Petróleo, 1999).

However, the most striking feature of this project was the participation of several local actors. Two of the most important were a mining training centre (TECSUP) that explored the feasibility of using the bacterial leaching technology to treat the mining tailings; and a domestic equipment producer (FIMA S.A.) that was responsible of 80% of the project's construction. Thus, Tamboraque became the first time that a mining project comprised a tight link between domestic agents.

In addition, for the first time in a small scale gold project, the mining firm produced doré bars (gold and silver lingots) that were sold directly to foreign refineries.

7.2 Technical background

The Tamboraque mine produced lead and zinc concentrates. The mine tailings had gold contents - i.e. 0.113 gold ounces per MT - and thus they represented around 60% of the mine assets. However, MLPSA could not recover the gold because of high arsenic contents. The firm had tried to produce arsenopyrite and gold concentrates, but the price cut because of the presence of arsenic was too high. Due to the lack of economic feasibility of recovering gold, the firm decided to store the tailings till they develop a way to economically recover gold.

In the mid-1980s, the technological advance in the treatment of gold minerals with arsenic content followed two paths. The first one was the toasting of concentrates that is the exposure of mineral to high temperatures to provoke chemical changes that allow the liberation of arsenic. The disadvantage of this technology was that is it very polluting because of the difficulty of capturing the arsenic particles released during the toasting process[72]. However, this technology was used in the Indio mine in Chile. The second one was the newly developed technology of gold leaching - both bacterial and cyanide-based. The bacterial based technology was being applied in the Fairview mine in South Africa that had set up a bacterial leaching (BIOX) plant with a capacity of 10 MT per day[73].

In 1984, the MLPSA Operations Manager and its metallurgic advisor hired an engineer who performed metallurgic research at Centromin --the Peruvian state-owned firm. This engineer had done a research fellowship in Russia and worked in a pilot plant that treated gold and arsenic concentrates, as well as participated in the Andean Pact project. He was given a sample of Tamboraque's concentrate and he, together with the firm's engineers, began the testing using bacterial leaching. In these tests, they reached a 75% recovery rate of gold. However, these results did not satisfy the firm's managers and the project was abandoned.

Between 1986 and 1988, the Belgian technical cooperation office donated some toasting furnaces to the National Institute of Geology, Mining and Metallurgy (INGEMMET). MLPSA and INGEMMET signed an agreement to perform toasting tests to eliminate arsenic. At the same time, some essays were sent to a Canadian laboratory to perform toasting tests and pressure leaching. The results in the toasting tests reached 60% of recovery. The bioleaching results proved to be more efficient since a 95.5% of gold dissolution was reached (Loayza, Glave and Ly, 1997). Thus, the firm decided to keep looking for other technological options in leaching. It is important to mention that MLPSA designated two engineers to act as technology gatekeepers.

Given those results, MLPSA thought of building a plant of 200 MT/day, but a pressure leaching plant is only profitable at more than 50,000 ounces per year. The South African firm Gencor (currently Gold Fields Ltd.), which patented a bacterial leaching technology, asked about US$ 1 million for licensing and US$ 600,000 for the tests. These investment requirements were too high for MLPSA, thus it abandoned the project.

Later on, TECSUP[74] - a technical training institute - received a leaching pilot plant on donation with the support of MLPSA. Then, it was possible to perform some experimentation with the Tamboraque mineral. A research team is formed with professionals coming from TECSUP and the mine. The results were satisfactory as it was possible to replicate the Gencor technology, but they were not sufficient to scale up the plant to an industrial size. Thus, the firm contacted again Gencor and asked for optimization studies and advise services in the neutralization of the cyanide residues.

Once the optimization of the process was done, it was possible to proceed with the plant's scaling up. The Peruvian branch of the engineering firm Kilborn is hired to design the plant. At that point, MLPSA began looking for sources to finance the US$ 23 million required to set up the plant. The domestic equipment producer FIMA was hired to be in charge of the largest share of construction (80%), but also helped to

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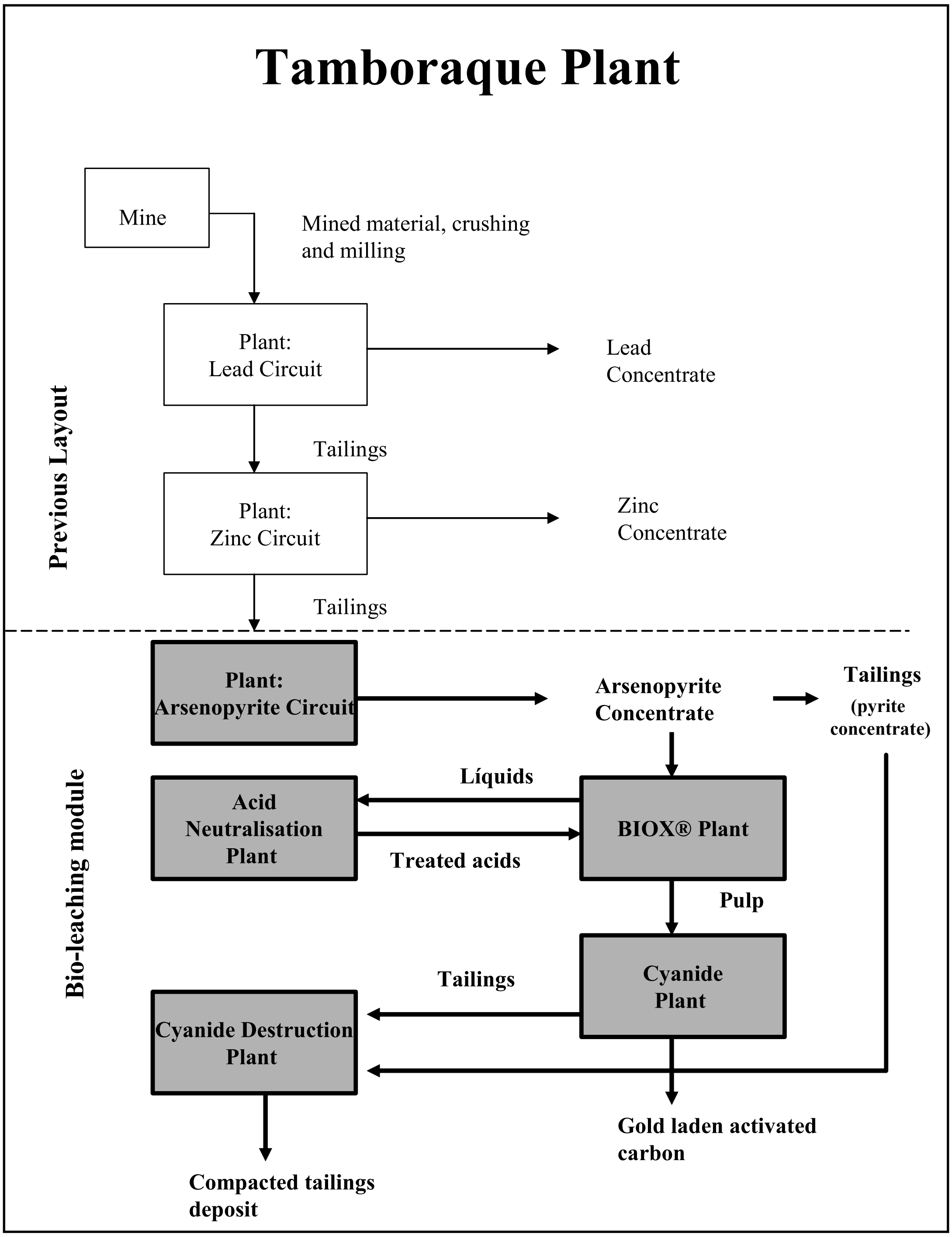
[72] It is important to mention that by 1931 MLPSA had a major conflict with local communities because of the toxic emissions from its smelting plant. The people in the communities tried to capture the plant but were expelled by the police. Unfortunately, around 9 people died and this event marked the difficult relations between the firm and the communities.

[73] At present, the Fairview plant has a capacity of 55 MT per day.

[74] TECSUP was created by the efforts of the mining entrepreneur Mauricio Hochschild. Mining and industrial firms find that technical education in Peru was not satisfactory, thus they supported the creation of this new institute that counted with the support of the German technical cooperation (GTZ). The flexibility of TECSUP made possible that firms ask for technical assistance, something very unusual to be asked to government institutions or universities.

look for other possible funding sources. Finally, MLPSA got the funding from two international financing funds, Repadre International Corporation (Canadá) y Global Environmental Emerging Markets Fund (Canadá), as well as from local banks. The construction of the plant began in 1997 and by early 1999 it was already operating.

Figure 14 - A description of the Tamboraque plant



Fuente: Elaboración propia basada en datos del MEM y (Minas y Petróleo, 1999c).

The Tamboraque plant had an annual capacity of 25,000 ounces of gold, 40,000 ounces of silver, 7,000 MT of zinc concentrates and 6,000 MT of lead concentrates with contents of 800,000 ounces of silver. This meant a daily treatment capacity of 200 MT.

The concentration plant was enlarged from 200 MT per day to 600 MT. The project included the addition of modules to the existing lead and zinc flotation circuits (see figure 14). The first module added was the selective flotation circuit to produce pyrite and arsenopyrite concentrates with gold content. The second module was the bio-leaching (BIOX) circuit, where the arsenopyrite concentrate was oxidised to allow the release of gold[75]. Oxidation occurs by the action of a mixed population of bacteria (i.e. thiobacillus ferrooxidans, thiobacillus thiooxidans, and leptospirillum ferrooxidans) that break down the sulphide mineral matrix, thereby liberating the occluded gold for subsequent cyanidation. The resultant pulp was sent to the cyanide circuit. The resulting liquids were sent to a neutralisation plant to treat acid solutions and further were sent back to the BIOX circuit. A carbon adsorption system captured gold. The laden carbon was sent to the firm Procesadora Sudamericana to obtain doré bars.

However, the prospects that supported the capacity increase soon prove to be over-optimistic. Mine reserves and ore grades fall short, thus it became very difficult to feed the plant, and production levels were lower than expected. MLPSA soon was unable to fulfill its financial obligations and broke down. The Tamboraque project was shut down and then transferred in 2001 to one of the banks that provided funding[76]. This change of administration cut all the research done in the operation, since the interest was on cutting costs and recovering the unpaid loan.

7.3 Absorptive capacity and technical capabilities of MLPSA

7.3.1 Acquisition

MLPSA had been operating for more than a century. During that period, the firm showed a capacity to make radical technological changes that required a capacity to run investment projects and to adapt to market changes, as well as technical expertise. These characteristics are difficult to find in a traditional family-owned mining firm in Peru. In fact, since its foundation MLPSA had shown special features.

It seems that since its beginning, MLPSA formulated an implicit technological vision and strategy that were focused in the incorporation of the latest technology by its time. One year after its foundation and as early as 1906, MLPSA built a small gold smelting plant. This happened five years later after the massive purchase of domestic mines by Cerro de Pasco Corp. Thorp y Bertram (1975) mentioned that Lizandro Proaño was one of the few domestic entrepreneurs that continued exploiting his own deposits. Later on, with the international increase of demand for base metals and the diffusion of the flotation technology, MLPSA decided to build a flotation plant in 1939. This plant had a capacity of 50 MT for processing lead and zinc ores and provided MLPSA with the flexibility of adapting to changes in the market conditions. In fact, in 1964, due to the low lead and zinc prices[77], the firm closed its mine and became a custom smelter. The latter reflected a capacity to deal with mineral with different metallogenic characteristics by adapting the flotation process. This knowledge of mineral ores seemed to be crucial to foresee that the gold encapsulated in the tailings was possible to be extracted. It is in the mid 1980s that MLPSA began searching technological solutions that lead to the construction of the BIOX plant.

These major investments executed by MLPSA required the existence of technological capacities within MLPSA. The firm's staff had to identify profitable market niches as

[75] For a complete description of the BIOX technology, see Annex 1.
[76] The bank asked Gencor to re-commission the plant and hired a mining consulting company to operate it. Conflicts with local communities forced again to shut down the plant. Some months later the bank hired another operator. But the conflicts continued and the plant was closed definitely in 2005, with a mine closure plan approved by the Ministry of Mining.
[77] Lead prices plummeted from US$0.20 per pound in 1951 to US$0.08 in 1963, and zinc prices went down from US$0.21 to US$0.10 in the same period.

well as evaluate, acquire and adapt new technologies in its existing operations. Some of the interviewed representatives mentioned that the firm assigned some engineers with the mission of gate keeping new technologies.

7.3.2 Assimilation

Assimilating knowledge about how to treat the gold bearing tailings took almost 10 years. MLPSA had two engineers that acted as technology gatekeepers and were aware of successful experiences of liberating gold from ores with arsenic content. Also, MLPSA engineers were in contact with professionals that had some experience with new technologies to treat complex metals. These contacts were crucial to get familiar with the bioleaching technology. Once the Glencor's BIOX technology was identified as a good solution, MLPSA found that it was too expensive for a small mining firm. Spillovers, in the form of public and informal sources of information, about this technology set the basis for MLPSA's technological capabilities in this technology. Even when the BIOX technology had already been patented, it served MLPSA to produce a new product and enter into a new market niche.

To assimilate this technology, MLPSA required performing tests to fully comprehend and learn the different processes involved. Thus, it was fundamental to have access to a pilot plant. Through contacts with staff members of Centromín Perú that participated in the Toromocho bioleaching project, MPLSA contacted a German expert who helped the firm to approach the German cooperation agency GTZ. This approach resulted in 1993 in the donation of a pilot leaching plant channelled to TECSUP, an industrial training centre.

With this donation, MLPSA began experimenting in-house and at TECSUP. One of the professionals contacted by MLPSA was in charge of the testing at TECSUP. His participation was crucial since he had previous experience in laboratories and in testing metallurgical technologies. The interaction with him provided all the participants in this venture with an intense learning experience that involved the socialization of tacit knowledge acquired by the different team members. An externalization process also took place, since the practical experience that the team members had to be articulated and codified. In fact, TECSUP recorded all the experience and prepared manual that further served as teaching and practice materials for its students. Finally, the experience allowed the combination of different bodies of knowledge, since it required a multidisciplinary approach.

It is worth mentioning that this was one of the few successful experiences of cooperation between a firm and an educational institution. Thus, learning was not only circumscribed to the firm's objective of optimizing the technology but also to TECSUP's interest to improve the training of students and the provision of research services to firms.

7.3.3 Transformation

In this stage, efforts were devoted to scaling up the plant and to adapting the existent operation to include the new bioleaching circuit. The two existing concentration circuits, lead and zinc, had to be adapted to include two additional ones, as shown in figure 14. The first one is the arsenopyrite circuit that produces arsenopyrite and pyrite concentrates. In addition, the bioleaching circuit demanded a complete new section in the plant. All these changes resulted in a very complex production layout.

Although the design and construction of the plant was commissioned to the engineering firm Kilborn, an intense socialisation took place in Tamboraque. Middle managers had to be informed and trained in the new technology, as well as had to adequate the other processes to optimise the operation of the whole plant. The interaction was so intense that the Kilborn chief enginner was hired by MLPSA and became the manager of MLPSA. Through intense experimentation, codified knowledge about bioleaching was transformed into established routines and know how (internalisation), as well as the regular routines have to be absorbed by the new bioleaching team. Also, the permanent incorporation to the firm of professionals that participated in different stages of experimentation made possible to integrate the tacit and codified knowledge. This intense socialisation was also possible because this mining operation was very small and had a very flat structure. Thus, both the formal and informal exchange of information was very fluid.

Socialisation continued after the new sections of the plant were finished. In fact, continuous experimentation in the bioleaching plant led to the identification of the bacteria acting in the bioleaching circuit. This provided a line of research to a biologist that worked in the bioleaching plant. Even when there was not a formal R&D budget to support the work with the bacteria, MLPSA provided the equipment and materials so the research would continue. The biologist focused the research in the ability of bacteria to adsorb heavy metals. It was expected that the identification of new strands of bacteria would catalyse the adsorption of gold from effluents, thus further extracting gold from tailings. However, the lack of public innovation funds made to change the focus of the project, so the biologist's strategy was to look for an environmental application that could be funded by a research fund.

7.3.4 Exploitation

By the time, the new plant entered into operation, all the MLPSA staff had increased their technological capabilities. The firm, as a whole, acquired solid core competences in bioleaching, but also improved their overall production capacities. For example, MLPSA was able to work in a close loop by using acid drainage as an input for bioleaching. This meant the reduction of production costs and the decrease of environmental risks. Another example is that MLPSA implemented a system of automatic control for the bioleaching circuit that was extended for the overall operation.

The 10-year search that took this technological solution had gained momentum when technological resources were available. Once the TECSUP pilot plant was set up and the tests were performed, the formulation of an investment project began. At this point, MLPSA devoted efforts to get international funding to initiate this venture.

The set up of the plant and its operation during more than 5 years proof that MLPSA was able to exploit the technology they replicated. However, the fact that MLPSA was not owner of the technology limited future developments to exploit this technology outside its operation. In fact, Gencor has cumulated evidence on more of 250 concentrate and whole ore samples about their compatibility with BIOX. Gencor also developed a project development framework to commercialise its technology. This framework includes BIOX amenability testing, pre-feasibility study, pilot plan run, process design package and basic engineering design, construction and commissioning (Goldfields, 2001).

In any case, the whole experience of setting up the bioleaching circuit had impact in the generation of additional capabilities with the expectation of future gains. MLPSA signed a research agreement with the École de Mines d'Ales in France to analyse the behaviour of bacteria in the adsorption of metallurgic tailings.

8 Lateral migration: from mining to environmental remediation

Although the concept of lateral migration is not well established in the technological innovation literature, it seems that it would fill a vacuum in the microeconomic explanation of knowledge transfer from one economic sector and/or knowledge field to another. At the microeconomic level, the analysis of firms' technology trajectories would shed some light on the process of adding knowledge to resource intense industries. At the meso and macroeconomic level, the analysis of the institutional framework may help understand if that addition of knowledge can contribute to an overall strategy of economic diversification.

This case study based on the experience of the Tamboraque project fulfils the requirement at the microeconomic level since it served to increase the technological capabilities in the firm and increase the knowledge level in the production process. It also provides some expectations about serving as a springboard to promote economic diversification since a bioremediation technology can be applied not only to polluted mining in the mine closure stage, but also to any other site whether the pollution is generated by industrial, agriculture or waste management activities, thus breaking the technology dependence on the resource-intensive industry. However, a full commitment from the different actors who conform the mining innovation system is necessary to realise this expectations.

As mentioned in the previous section, the identification of bacteria in the leaching process led to look for other applications. The biologist said that the use of bacteria for metal extraction (bioleaching) is the other side of the coin of the use of bacteria for remediation, it is the same function. Bacteria grow natural in environments where leaching takes place. Bacteria colonies host different kind of species. Some of them eat iron, such as the thiobacillus ferroxindans and help to break the molecules of sulphur ores and liberate copper. Some others behave well at high temperatures and are appropriate to treat complex minerals in autoclaves. Thus, it is important to identify which bacteria are present in different settings to understand the chemical reactions that take place.

Table 12 - Bachellor theses on bioadsorption at Universidad Particular Cayetano Heredia

Peirano, Francisco (2001). "Auric Gold Sorption by Chitosan Polymers: Modelling and Chinetics". Currently pursuing PhD studies in the École des Mines d'Ales - University of Marseille, France.
Rojas, Graciela (2002). "pH Influence, Weight of Chitosan Bio-polymer and Chromium Concentration in the Speed of Sorption of Chromium Trivalent and Hexavalent Ions: Modelling and Chinetics". Currently working in the Environmental Department at the Alto Chicama operation (Barrick).
Flores, Jaime (2003). "Copper (II) Biosorption by Chitosan, Reticulated Chitosan with Glutaraldehid and Chitosan in Pearls". Currently pursuing graduate studies in the US.
Navarro, Abel (2004). "Selection of the Best Bio-adsorbent for Cadmium (II) Ions: Modelling of Balance and Chinetics". Currently pursuing graduate studies in the US.
Campos, Karol (2004). "Selection of the Best Bio-adsorbent for Zinc (II) Ions: Modelling and Chinetics". Currently pursuing a Master Degree at the École des Mines d'Ales - University of Marseille, France.
Ramos, Karim (2004). "New Bio-adsorbents for the Sorption of Cadmium from Aqueous Solutions".

A research agreement signed between MLPSA and the École de Mines d'Ales made it possible to begin studies in this new line of inquiry. The use of a catalyst, such as chitosan[78], in contaminated soils where the tailings had been piled could increase bacterial activity and help to extract the remaining gold. Another possible advantage was to transform the mineral contained in tailings into minerals that have a more stable chemical composition, thus reducing its polluting hazard.

[78] Chitosan is a polymer produced from crab shells.

Unfortunately, the financial pressures that led to the commercial failure of Tamboraque prevented these studies to continuing. However, the biologist continued her relation with the École de Mines d'Ales and with her affiliation at the Universidad Particular Cayetano Heredia, while combining her professional practice at different mining consulting firms. She spent some months in France doing some research and then came back and joined some research groups in Peru. The biologist has acted as thesis advisor for biology graduates in the area of adsorption. Table 12 shows that since 2001, six theses have been done on topics related to bio-adsorption. Most of the students are pursuing graduate studies in different universities in France and the United States. The two students that are studying in France continue doing research in bio-adsorption.

The biologist is conscious that the multidisciplinary approach should be used in bioleaching research. For that reason, she has forged relations with Chemistry professors at Universidad Nacional Mayor de San Marcos and with Metallurgy professors at Pontificia Universidad Católica del Perú. Furthermore, she has been contacted by members of the Chilean Genome programme to collaborate in the bio-mining subproject.

Besides the publication of papers in specialised journals, the biologist has just received a grant to apply her studies in the cleaning up of a mine and water bodies. This will be the first time that such a technology is used outside a laboratory. The recent setting up of a genomics laboratory at the Universidad Particular Cayetano Heredia will make it possible to begin isolating and classifying new strain of bacteria involved in the bioleaching and bioadsorption processes. Another colleague will begin doing the molecular identification of bacteria. These projects are in the pipeline and additional funding is being searched.

9 The limited action of the Peruvian mining innovation system

An innovation system refers to the different institutions, firms and government that conform to the scientific and technological apparatus, and to the way these agents interact in the creation, diffusion and utilization of knowledge. In Peru, as well as in many developing countries, innovation systems are very fragmented and it is even difficult to talk about a system. Mullin Consulting (2003) claimed that the different parts of the system do not interact in a constructive way but instead compete among themselves. Thus, the incentives behind this system are perverse and have a negative effect on knowledge diffusion.

Within the mining industry, the innovation system is composed by the firms, universities and research centres and government institutions. Mining firms in Peru are heterogeneous. They differ in their size and technological capabilities, since multinational subsidiaries exploit large deposits and mineral processing plants, using cutting-edge technology; while there are also small scale and artisanal operations that use obsolete technology. In the middle, there are medium firms that use mature technology. Firms also differ in the deposits they exploit, some firms exploit copper, gold or tin; while others exploit polymetallic deposits.

This diversity renders into different technological behaviours. Large firms, which are connected to international funding sources, will solve their technological problems relying in expertise outside Peru, usually in their home countries. Small and medium-size firms usually demand technological services to domestic providers, but their financial constraints impede the growth of this demand. Firms, in general, are interested in gaining operative efficiency but not in making radical changes. MLPSA was an exception to the rule.

Universities and research institutes, on their side, have worked isolated from firms. They have traditionally done their research without taking into account the needs of the productive sector. It is only in the last decade, that budget reductions have forced them to look for clients in the private sector (Mulling Consulting, 2003). However, very few of them have succeeded, sometimes because they have different visions of what research involves or because they do not have the capabilities to solve day-to-day problems. In this regard, the collaboration between TECSUP and MLPSA was very unusual.

Government institutions are usually devoted to promote mining in terms of increase of output, without considering technological advancement and efficiency. In that sense, some regulatory bodies, such as the Mining Cadastre or the Environmental Office, focus on administrative work but do not actively promote the use of new technologies to improve their work[79]. Even more, since 1993 the INGEMMET functions have been limited to geological activities, such as the culmination of the Geological Map, although the name of this institute still mentions the words mining and metallurgy[80]. Finally, as opposed to a previous Mining Law, in the current Mining Code there is no mention of the word technology.

The typical behaviour of these three sets of actors is to work in isolation. Even though when the annual Mining Conventions serve as a common arena where a lot of information is exchanged, the kind of information is very limited and cooperation agreements or projects are seldom pursued. This behaviour poses a serious restriction for knowledge generation and diffusion. In fact, one of the reasons why the Chileans developed sophisticated capacities in hydrometallurgy is that universities got involved quite early in the efforts of technology development[81]. Beckel (2001) reported that one of the entrepreneurs responsible for the development of bacterial leaching in Chile[82] introduced the theme as part of the curriculum in the university where he taught, as well as allowed part of his staff to teach in other universities. "This teaching activities generated a series of theses that were useful for his own firm and also contributed to awake within the universities an interest for basic and applied research in this field" (Beckel, 2001; page 124; free translation from the authors). In 1985, a large project for developing biological processes and promote their industrial application in Chilean copper ores was funded by UNDP. This project was proposed jointly by a group of academic and technological institutions and firms. This collaborative project made possible "the development of an inter-disciplinary national team, with knowledge on copper leaching similar or even better to that existing in any other international scientific and technological community" (Beckel, 2001; page 125; free translation from the authors).

[79] The Mining Cadastre Office has 6 administrative functions (see URL: http://www.inacc.gob.pe/). The Mining Environmental Office has 13 functions but none of them deals directly with promoting technological change for a better environmental management (see URL: http://www.minem.gob.pe/dgaam/proced_inicio.asp).

[80] There is a flagrant contradiction in the INGEMMET web page. After mentioning that since 1993 this institution will no longer have mining or metallurgical activities, its list of functions include the diffusion of new mining and metallurgical technologies (see URL: http://www.ingemmet.gob.pe/presentacion_institucional/funciones.htm).

[81] By the time the Andean Pact project was launched, Chileans initiated a parallel project and kept some communication with the Peruvian and Bolivian teams.

[82] Esteban Domic was the owner of Sociedad Minera Pudahuel (SMP), firm that patented an application of bacterial leaching in 1981. During the first half of the 1990s, SMP provided technological services (paid and for free) to different mining firms and, as a result, its leaching technology was applied in 16 new mining operations (Beckel, 2001).

With regards to the incentives within the Peruvian innovation system, administrative red tape becomes a great constraint. Researchers in public universities have serious problems when they get external funding for their research. Funds are usually required to be administered by the general treasury office, thus limiting the flexibility of researcher to hire research staff or make expenditures. Red tape not only affects funds administration but also the use of infrastructure. Some university labs remain underutilised while researchers in other universities cannot do their work because of lack of equipment (Mulling Consulting, 2003).

Finally, there are no incentives to promote innovation in the private sector. Mining regulation offers tax incentives to increase exploration or to promote new investment. However, the system does not provide any motivation to firms that perform R&D in their operations. The only incentive for technological change in the mining sector is the exoneration of tariffs for equipment. It is obvious that the innovation system described above does not promote the generation, adaptation, transfer and diffusion of knowledge, as apposed to the one existing in Chile. Thus, it is understandable that major technological advances such as the Andean Pact projects or the Tamboraque experience remained unnoticed for the different actors in the Peruvian mining sector.

10 Final comments

This paper has presented a case study that could be classified as a lateral migration from the mining sector to that of environmental services. In this case, lateral migration would be realised because the new service does not maintain any dependence with the original natural resource (mineral ores). Even when bacteria are specific to the location and the nature of the mineral deposit, the knowledge generated in the use of this bacteria is generic and can be used in different settings. In that sense, the remediation technology can be applied not only to polluted mining in the mine closure stage, but also to any other site whether the pollution is generated by industrial, agriculture or waste management activities. The important knowledge to be recovered is the classification, management and genetic alteration of bacteria. That knowledge can be easily transmitted to other uses.

This case study presents a lateral migration that is not completed yet because of the early stage of development of the technology, however there are promising prospects that a generic technology may grow from the efforts described in this case study. The study has also reflected that the Peruvian innovation system is not fulfilling its functions of generating, diffusing and promoting the use of knowledge in the economy, and this poses a major constraint to the realisation of the technological migration.

Fortunately, recent interest from the government to promote science and technology activities that were previously long neglected may change the previous situation. Some indications of this change are the inclusion of mining as a priority area of study in the National Science and Technology Plan, and the launch of a innovation fund that will support projects from firms and promote collaboration among the prior and universities and government technological institutions. However, these changes will need to be coordinated with changes in the Peruvian mining legislation. The sectoral focus on promoting private investment must be widened to include technological change.

One specific regulatory area that might aid the migration is that of remediation of mining sites. The current legislation declares that the State is responsible for the remediation of orphan polluted mining sites and declares that some funds will be available for this purpose. This would provide a good opportunity to test this bio-remediation technology.

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12 Annex 1

BIOX®

Ashanti Goldfields, Ghana, the largest BIOX® plant in the world.

For the treatment of refractory gold ores:

- Increased gold recovery rates
- Robust technology
- Environmentally friendly
- Commercially viable and cost effective

The BIOX® process, which pre-treats refractory sulphide gold ores such as pyrite, arsenopyrite and pyrrhotite, was developed to increase gold recovery rates during the metallurgical extraction process. The gold in these sulphide ores is encapsulated in sulphide minerals which prevent the gold from being leached by cyanide. The BIOX® process destroys the sulphide minerals and exposes the gold for subsequent cyanidation, increasing recovery rates.

The BIOX® process has many real advantages over conventional refractory processes such as roasting, pressure oxidation and nitric acid leaching. These include:

- Improved rates of gold recovery
- Significantly lower capital costs
- Low running costs
- Robust technology that is suited to remote areas
- Low level of skills required for operation
- Environmentally friendly
- Ongoing process development and improvement

Rights to the process, which has been available commercially for more than 15 years, are currently held by Biomin Technologies SA, a subsidiary of Gold Fields Limited. However, the initial research and development into the process was conducted by Gencor Process Research (now Billiton Process Research).

The BIOX® process

The process itself uses a combination of three bacteria that occur naturally, thiobacillus ferrooxidans, thiobacillus thiooxidans and leptospirillum ferroxidans, to break down the sulphide mineral matrix in the ore being treated, thus freeing the occluded gold for subsequent cyanidation. The bacteria attach themselves to the metal sulphide surfaces in the ore, resulting in the accelerated oxidation of the sulphides.

The BIOX® process involves the continuous feeding of the flotation concentrate slurry to a series of stirred reactors.

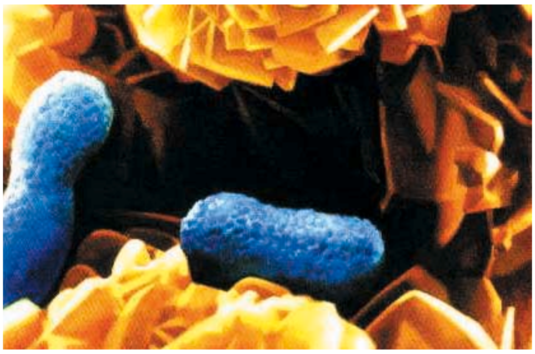
Low pH levels and a high slurry temperature enhance the efficiency of the process and it is important that these parameters are controlled within narrow ranges so as to maintain the right balance of bacteria in order to achieve the optimum rate of oxidation.

The reactors are aerated and the slurry temperature is maintained at the optimum level of 40-45°C. As the oxidation reactions of sulphide minerals are exothermic, it is necessary to cool the tanks so as to maintain the slurry temperature within the optimum range. This is done by circulating cooling water and removing the excess heat via a cooling tower.

The pH level is controlled by adding limestone or sulphuric acid to the slurry. Since direct sulphide oxidation requires high levels of oxygen, large volumes of air have to be injected and dispersed in the slurry. This is one of the main engineering challenges in the design of a full-scale bio-reactor.

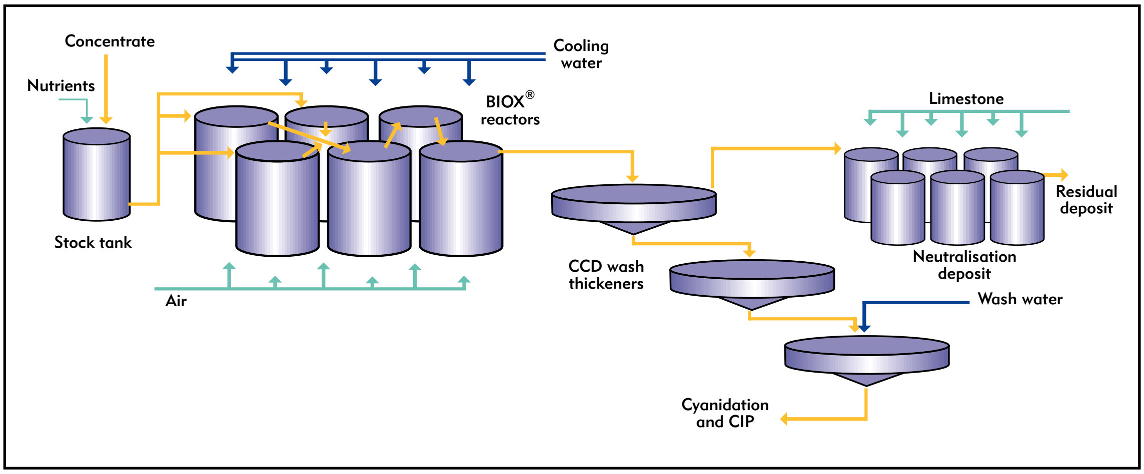
Furthermore, sufficient carbon dioxide is required for the bacteria to maintain cellular growth. This is obtained from the injected air as well as carbonate minerals. Should the latter be absent, limestone is added.

The bacteria also require nutrients to sustain growth. Nitrogen, phosphorous and potassium are added to the primary reactors in various forms and quantities, depending on the composition of the concentrate being treated.



A photomicrograph of the thiobacillus ferrooxidans bacteria which is a component of the bacterial culture used in the BIOX® process.

Flow diagram of the BIOX® process



The overall residence time in the bio-oxidation reactors, which is mainly a function of the mineralogy, typically varies between four and six days. For an ore where the gold is locked mainly in arsenopyrite, a shorter residence time is expected to achieve optimum gold liberation than with an ore where most of the gold is occluded in pyrite. This is because the oxidation rate of arsenopyrite is faster than that of pyrite.

Some ores require only partial sulphide oxidation to liberate the gold. The circuit can be simplified for such ores and the residence time reduced to two days or less.

During the bacterial oxidation process, elements like iron, sulphur and arsenic are dissolved. After oxidation, the BIOX® product is washed in a counter-current decantation circuit and the solution is neutralised in a controlled two-stage process with limestone and/or lime. The precipitates formed meet environmental standards set in the United States and can be safely deposited onto tailings dams. The BIOX® process is thus a non-polluting, environmentally clean means of treating refractory ore.

To save water, the neutralised effluent can be mixed with flotation tailings and thickened. The overflow solution can be recycled as dilution water in the milling, flotation and BIOX® sections of the plant. This makes the process ideally suited for arid regions.

The washed BIOX® product is treated in a conventional cyanidation plant from which the gold is finally recovered.

Operating parameters of the BIOX® process

Temperature:	40-45°C
pH:	1.2-1.6
Percentage solids in feed:	20%
Dissolved oxygen:	>2ppm
Retention time:	4-6 days
Nutrients	fertiliser type ammonium, potassium and phosphorus salts

Plants in operation

Four BIOX® plants are currently in operation – in South Africa, Ghana, Brazil and Australia – with the most successful of these being Ashanti's Sansu plant near Obuasi in Ghana. The Tamboraque plant in Peru is currently being recommissioned.

The Tamboraque plant in Peru is currently being recommissioned.

Ashanti, Ghana

Ashanti Goldfields Company investigated several refractory treatment options including roasting, pressure oxidation and nitric acid leaching. The BIOX® technology was selected for, among other reasons, its lower capital and operating costs, reduced technical risk, relatively benign environmental impact and its ease of operation.

Designed with an initial capacity of treating 720 tonnes of concentrate per day, the Sansu plant has since been expanded and currently has four modules processing 960 tonnes per day in all. It is by far the largest bio-oxidation plant in the world and its modular design makes it possible to apply the technology to large refractory deposits. The simplicity of the process also makes it ideal for remote areas.

Furthermore, the metallurgical performance of the Sansu BIOX® plant has been highly satisfactory in coping with the local ore of which there are two types, which differ widely regarding their mineralogical and bio-oxidation characteristics. This demanded a plant design with sufficient flexibility to treat both concentrates, either individually or as a blend.

The capital cost of the plant totalled US$25 million (1994 terms) and the operating cost is currently US$17/tonne milled.

Fairview, South Africa

The BIOX® plant at the Fairview mine in Barberton, which was the initial pilot plant, has been fully operational for 15 years. It was originally designed to treat 10 tonnes a day but with the success of the project this has been increased over time to 55 tonnes of concentrate per day.

Much of the innovative research work on the bio-oxidation of refractory gold ores conducted in the late 1970s and early 1980s was driven by the need to replace the outdated Edward's roasters at Fairview, which at the time were seriously contributing to atmospheric and water pollution in the environmentally sensitive Barberton area of South Africa.

This plant has played a vital role in the ongoing development of the BIOX® process as the scale of the

The Fairview BIOX® Plant in Mpumalanga province, South Africa, which currently treats 55 tonnes of concentrate a day.

operation has lent itself to the testing of new equipment, design modifications and process optimisation.

With the purchase of Fairview by Avgold Ltd's Eastern Transvaal Consolidated, Avgold concluded a licensing agreement with Gold Fields entitling it to use the BIOX® technology to treat its concentrate. Gold Fields has retained access to the plant and site to enable it to continue its development work and train operators for new BIOX® plants.

The plant has been both a technical and commercial success, confirming the simplicity of the process and the robustness of the technology.

Sao Bento, Brazil

A BIOX® plant is also in operation in Brazil at the Sao Bento Mine where a pressure oxidation circuit is used to treat the refractory flotation concentrate. This plant has confirmed the viability of combining bio-oxidation with pressure oxidation as a cost-effective method of increasing capacity at an existing oxidation plant.

Wiluna, Australia

The fourth plant, in operation at Wiluna Gold Mine, Western Australia, was commissioned in 1993. Although originally designed to treat 115 tonnes per day of concentrate this has subsequently been increased to

The BIOX® plant at Wiluna Gold Mine, Western Australia, whose reserves are mostly refractory sulphides.

158 tonnes per day. Since the cost of power initially amounted to 50% of the operating costs, a natural gas-fired power station was built to replace the diesel generation and limit costs.

Future developments

To date more than 250 concentrate and whole ore samples have been tested for compatibility with the BIOX® process and more than 15 integrated pilot plants to monitor and refine the design of commercial plants have been completed. One such pilot plant, together with a detailed commercial process design, was completed for Golden Star Resources Bogoso Mine in Ghana.

Currently, several projects are at the feasibility stage or awaiting financial backing. In addition, technology licence agreements have been signed with gold mining companies in Uzbekistan, Greece and Australia. Of these, the largest project is that in Uzbekistan where the agreement with the Navoi Mining and Metallurgical Combinat is for a BIOX® plant with an ultimate capacity of 2,055 tonnes of concentrate a day.

Project development framework

	Requirements	Duration	Results
BIOX® amenability testing	10 kg concentrate 10 litre process water	2.5 months	Detailed report with: Rate of oxidation Gold recovery vs oxidation
Pre-feasibility study (optional)	Treatment rate Concentrate grade Unit cost data	1 month	Conceptual flow diagram Preliminary equipment list Order-of-magnitude cost estimates
Pilot plant run	Testwork agreement 1,000 kg sample	4 months	Detailed report with: Design parameters Reagent consumptions Operating strategy
Process design package	Licence agreement Key design criteria	1 month	Process design specifications Mass balances Process flow diagrams
Basic engineering design, construction and commissioning	Approval of contractor	9 - 12 months	Bacterial inoculum Operating manual Operator training Plant commissioning On-going technical support

GOLD FIELDS

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An analysis of hydraulic technologies in South Africa's mining sector

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February 2006

Chapter 5: An analysis of hydraulic technologies in South Africa's mining sector

Abstract

This paper examines a co-operative initiative undertaken by South Africa's gold mining companies through the Chamber of Mines Research Organisation (COMRO) in development of hydraulic technologies for mining in South Africa. After a brief description of the structure of these technologies development under COMRO's stewardship, the paper turns to an overview of the system of innovation. We highlight the important contribution of industry initiative and State policies in drawing domestic capabilities together with international expertise to develop this technology. These hydraulic technologies were at the international forefront in their development. However, to date the technology has only diffused in a limited way to other mining applications and less so in other non-mining applications. We examine reasons for the success and failure of hydraulic technologies, showing that while there remains huge potential for diverse application of the technology there is no certainty that that application will occur or have a significant impact on South African expertise.

Acronyms

AAC	Anglo American Corporation (AngloGold Ashanti Limited)
COMRO	Chamber of Mines Research Organization
COMSA	Chamber of Mines of South Africa
EH	Emulsion Hydraulic
GFSA	Gold Fields South Africa (Gold Fields Limited South Africa)
GPC	Gold Producers Committee
HH	Hydro-hydraulic
HSRC	Human Sciences Research Council
kPa	Kilopascal (1,000 Pa)
MPa	Megapascal (1,000,000 Pa)
Pa	Pascal
R&D	Research and Development
RA	Research Advisor
RAC	Research Advisory Committee
S&T	Science and Technology
TA	Technical Advisor
TAC	Technical Advisory Committee
TRAC	Technical and Research Advisory Committee
U.K.	United Kingdom
U.S.	United States

> "I presented the 2004 Technology Top 100 award for 'Outstanding Technological Innovation' to a company that has developed a sophisticated heavy-duty pneumatic rock drill. This is Sulzer Pumps and its hydro-mining division. They have developed a world first technological capability to drill with water rather than oil as the lubricant. Of special significance is that this achievement addresses a number of health and environmental issues in the mining industry. This innovation has the potential to revolutionise the entire drilling industry, from mining to construction."
>
> Mr. Mosibudi Mangena, Minister of Science and Technology, 22 November 2004

1 Introduction

This case is part of the Human Sciences Research Council (HSRC) Lateral Migration Project. Focus is on a set of hydraulic technologies developed between the 1960s and 1990s. Through a co-operative initiative of South Africa's gold mining companies these technologies created international markets for both equipment suppliers and mining consultants associated with their development.

Section two begins our analysis with a description of the development of hydraulic technologies. Two distinct stages of hydraulic technologies' are identified. First, emulsion hydraulic (EH)[83] technologies were developed and commercially deployed between the mid-1960s and the late 1980s. Second, water or hydro-hydraulic (HH)[84] technologies were developed and commercially deployed between the early 1980s and the early 1990s. While overlapping, the EH technologies were an important step in a learning process that eventually led to EH technologies displacement by HH technologies. Section two also highlights inter-relationships among hydraulic drilling and hydraulic power technologies. These applications symbiotically led to the eventual development of a suite of commercially viable hydraulic equipment and consultancy services.

In Section three, attention turns to the structure of innovation within which these hydraulic technologies were developed. The primary organization responsible for development of these technologies was the Chamber of Mines Research Organization (COMRO). COMRO's creation and eventual dissolution corresponds closely to the initiation and conclusion of research into hydraulic technologies.[85] Therefore, Section Three examines some reasons for the creation, transformation, and eventual dissolution of COMRO. The Section concludes with an evidence-based reflection on whether similar technologies are likely to emerge in the present system of innovation.

Section four examines the evolution of HH technologies and their demand since the dissolution of COMRO. In line with the focus of this project, the section is divided between the evolution and demand for HH technologies in its original market and HH technologies evolution and demand in alternative markets. In the original market HH technologies today form the core business of several South African based equipment manufacturers. Several mine consulting services firms also had linkages of varying strengths to HH technologies. Today, with several years of relatively stagnant demand for new systems based on HH technologies, these firms in the service sector find HH technologies have an ancillary role in their operations.

There are a host of other applications for HH technologies besides mining. Internationality, these technologies have also played an important role in the development of mining service organisations and equipment suppliers in a range of

[83] Emulsion hydraulics involves mixtures with non-soluble oil finely dispersed in water.
[84] Hydro-hydraulics involves no oil and just utilises water.
[85] Nonetheless, hydraulic technologies continue to be refined and developed by equipment manufacturers.

other activities. In many instances these indirect markets have already or promise to surpass in importance the direct application of the COMRO developed technologies. As such, this indirect migration illustrates another important dimension to the migration of technologies and the potential benefits of technology support initiatives.

The final section brings the analysis full circle by reflecting on evidence from this case on key dimensions that describe lateral migration. These dimensions consist of the absorptive capacity of firms, the role of foreign technology transfers, the role played by networked relationships, and the role played by industrial and innovation policy. This paper thus provides important evidence of lateral migration in South Africa's economy. In addition, it provides a previously undocumented history of the evolution of a major feature of the system of innovation in South Africa's mining sector.

2 Development of hydraulic technologies[86]

The development of hydraulic technologies originated within a much broader effort to decrease the labour intensity of gold mining on the Witwatersrand. Referred to as 'mechanization', this transformation began to be expressed by the mining industry in the late-1950s.[87] In the 1920s, Witwatersrand mining had transformed stoping practices underground through the introduction of pneumatically powered rock drills.[88] In order to facilitate replacement of predominantly expatriate white miners with this technology, the mines committed themselves to racial occupational mobility restriction over Black miners.[89]

As existing goldmines went deeper and new fields in the Far West Rand and Orange Free State were developed over deposits beginning at ever-increasing depths, the racial occupational mobility restrictions created ever-increasing burdens on the industry. With a legacy of internal racism and a broader political economy of racial discrimination impeding any likely removal of occupational mobility restrictions, mechanization offered the Witwatersrand gold mining industry a means to increase the efficiency of production. Greater output per worker under ground along with the static real wage being paid to Black miners at the time meant that the higher costs of production at depths could be covered.[90]

Previously, many of the technologies that changed the Witwatersrand gold mining industry had been developed by the mining-finance groups. In the 1950s, as some of the traditional technological leaders diversified out of Witwatersrand gold mining, COMSA became an increasingly important player in the industry's research activity.[91] Despite some misgivings and institutional rigidities favouring technical or engineering

[86] This section benefited from discussions with George Harper, Peter Hes, Noel Joughin, Geoff Minnitt, Mike O'Connor, Alex du Plessis, Julian Wills, and Denis Wymer. However, this section is not, necessarily, a reflection of their opinions and inaccuracies that exist are the authors'.
[87] See Black and Edwards (1957) and Hamilton (1963).
[88] Stoping practices are the underground operations removing the gold bearing host rock (reef). Underground mining uses tunnels, dug horizontally from the shafts, to access and transport the reef. The actual work area where the reef is extracted is called the stope. The basics of shaft digging, tunnelling, and stoping are similar processes; involving drilling small holes (blast holes) into the hard rock, planting and detonation of explosives in these blast holes and then clearing the blasted material..
[89] See Johnstone (1976).
[90] Wilson (1972) shows that the real wage paid to Black miners was static between the 1920s and early 1970s.
[91] For instance in 1954, COMSA took over rock burst research that had previously been conducted under a collaborative research partnership between the mining-finance groups and the CSIR.

sciences, COMSA established COMRO in 1964 with a linear focus on scientific research feeding into technological development.[92]

Shortly after its formation in 1965 COMRO established a new Mining Research Division (MRD) tasked with developing technologies to improve the efficiency of underground gold mining operations. The MRD marked the beginning of co-ordinated research by the industry into development of underground mining technologies. However, two changes in the early-1970s to the structure of the gold market led COMSA's Gold Producers Committee (GPC) in 1974 to commit COMRO to a large systematic ten-year research initiative into the development of mechanization technologies for operations underground.[93] First, African nations in a post-colonial setting threatened the supply of relatively inexpensive Black miners from across Southern Africa.[94] Between 1973 and 1976, the number of foreign workers on the Witwatersrand gold mines dropped from 336,000 to less than 200,000 (Crush et al. 1991, p. 101). Second, in 1971 the United States abandoned its underwriting the fixed-price of gold leading to a marked appreciation. Between 1971 and 1973, the real annual compound price of gold in Rand rose at a rate of 42.4%.[95] As operating under the racial occupational mobility restrictions fundamentally constrained production efficiencies, particularly at ever increasing depths, and with little short-term solutions, the industry turned to the mechanisation programme as a means to access the Witwatersrand deposits that continued deeper underground.

2.1 Development of emulsion hydraulic technologies

Table 13 lists important dates in the development of hydraulic technologies. From the mid-1960s to the early 1970s, initial research into underground technologies by COMRO focused on alternative technologies for stoping. None of these technologies was of direct importance to the subsequent development of hydraulic technologies in mining operation. Nevertheless, because many of these technologies had significant power and energy requirements, they contributed to COMRO investigating hydropower as an energy source.

[92] See Section 3.1 for details on the creation of COMRO and its predecessors within COMSA.
[93] Besides stoping technologies, this research program also investigated environmental and safety technologies, mining operations, and human resources.
[94] See Spandau (1980) and Hermanus (1988).
[95] See table 17 in Chapter 4 for details of historic trends in the price of gold.

Table 13 - A selection of important dates in the development of hydraulic technologies (1965-1991)

1965	COMRO Mining Research Division established
1973	Hydro-power as energy source investigated
1975	Chilled water service for mine cooling begins production trial (completed 1977)
1975	COMRO & Ingersoll-Rand begin developing 95-5 drill
1975	COMRO & Vickers Systems begin developing 95-5 power system
1977	First prototype 95-5 drill tested at West Driefontein gold mine
1978	COMRO begins additional 95-5 power system development with Hammelmann
1979	Second prototype 95-5 drill tested at West Driefontein gold mine
1980	COMRO & Ingersoll-Rand develop quadruple plunger rotation mechanism for drill
1980	COMRO initiates research into combined hydraulic power and cooling systems
1982	Ingersoll-Rand production model 95-5 drill (tested West Driefontein June 1983 to March 1984)
1982	COMRO begins developing 98-2 & HH drills with Ingersoll-Rand, Seco, and Novatek
1983	First Prototype 98-2 power system developed (tested Kloof goldmine 1984)
1985	First Prototype HH power system developed (tested at Kloof goldmine 1985-1986)
1986	98-2 drills begin production tests in Far West Rand and Orange Free State gold mines
1987	COMRO leaves subsequent development of 98-2 drills to Ingersoll-Rand, Seco, & Novatek
1987	COMRO draws Crown Chrome Plating into hydraulic pump research as Vickers phased out
1988	COMRO working with equipment suppliers to develop open system of hydro-power & cooling
1989	Production models of 98-2 drills available
1980	Sulzer joins in COMRO hydraulic drill development initiative
1991	Production models of HH drills available

Source: Compiled by authors

Just before initiating the ten-year mechanization research and development (R&D) programme in 1974, William Rapson, COMSA's Research Advisor (RA) and COMRO's Director was replaced by Miklos Salamon. Thus, as COMRO's annual budget increased three fold, Salamon realigned COMRO's organisational structure to the mechanisation research programme. The mechanization research programme became COMRO's R&D ethos until the organisation's dissolution nearly twenty years later.

COMRO's strategy in developing stoping equipment was to maintain a critical stock of knowledge internally in order to ensure continuity in the technology's development. While maintaining that stock, COMRO sought to outsource its R&D to equipment suppliers, other research organizations, and South African Universities (Joughin, 1982). Nonetheless, a majority of basic research and early technical trials were done by COMRO itself. Collaboration with equipment manufacturers was emphasized and driven by several organizational priorities. Firstly, COMRO did not want to build itself into an equipment supplier, it also wanted to ensure market viability of its technologies and incorporate manufacturing know-how into the technologies' development as well as realize economies of scale and speed in development of the technologies through the broader base of all participatory organization. Lastly, collaboration focused on equipment manufacturers with local operations so that "…through the participation of manufacturers in the development it was hoped to encourage the timeous evolution in this country of a viable industry manufacturing mining equipment to supply the eventual requirements of the mines" (Salamon, 1976, p. 71).

Following a linear model of innovation,[96] when a technology's feasibility for development was established COMRO would involve equipment manufacturers. Working together closely in design, the manufacturers were responsible for construction and COMRO was responsible for evaluation. Rights for development of the technologies were vested with COMRO. As the hydraulic technologies were perceived to be high-risk, COMRO entered into a contract with equipment manufacturers where COMRO paid their costs plus a five percent premium, effectively bearing the costs of design, construction and evaluation.[97]

When more than one equipment manufacturer was involved in the development of a particular technology, COMRO would not exchange or transfer data about other equipment's performance between organizations. However, COMRO did advise each company whether a problem was unique to that company or if it had been experienced by one or more of the other companies. If a similar problem had been encountered by another partner, COMRO would advise whether a solution had been found. Thus, as we shall see later, this collaborative system structurally favoured late entrants because it made technological catch-up less burdensome than original development.[98]

The 1974 mechanization research programme consisted of two distinct groups of technologies: 1) conventional and 2) revolutionary. The conventional technologies focused on improving existing mining methods and under it, the hydraulic drill program fell. The revolutionary approach focused on changing the way of mining by moving from stoping by drilling and blasting to continuous mining with various methods of mechanical rock breaking. Early in the revolutionary technologies research, one of the most promising technologies was the drag-bit miner.[99] A drag-bit miner operates in manner similar to a chain saw, but it cuts with a large cylinder upon which rows of metal spike are mounted. The spiked drum is then driven into the host rock to break out the gold bearing ore. This promise of the drag-bit miner would be important as high-pressure water jets, around 30 mega Pascal (MPa),[100] were found to greatly increase its cutting efficiency (Hood, 1976). Emulsion sprays were simply not viable underground from both an environmental and economic perspective, so an early force for a pure water (hydro) system emerged.

In conventional technologies, alternatives for both pneumatic power and pneumatic equipment were sought because of the increasingly deep and fractured conditions underground.[101] Therefore, hydraulic technologies were investigated as alternatives to pneumatic technologies. Marshall (1975) gives a summary of early advantages and disadvantages of hydraulic technologies. In terms of energy efficiency, hydraulics had about a 30% rate of efficiency at the stope face compared to 10% for pneumatics. The physical law, force equals pressure times area, governs the power of a drill. Since, a functional maximum pressure for pneumatic equipment was reached at around 200 kilopascal (kPa),[102] hydraulic technologies with their greater range of pressures promised to deliver more power to the stope face. In addition, hydraulic drills have a stress wave of uniform amplitude. Therefore, a blow from a hydraulic drill with the same energy as a pneumatic drill has significantly less peak stress or for the same peak stress in a hydraulic drill there is a much higher energy content, both of which

[96] For a critique of linear models of innovation see Kline and Rosenburg (1986).
[97] COMRO also had a 'low-risk' contract where equipment manufacturers bore design and construction costs while COMRO bore the cost of evaluation.
[98] For an explanation of why this would facilitate catch-up see Perez and Soete (1988).
[99] Other revolutionary technologies experimented with during this era were rock-cutters, swing-hammers, impact rippers and armoured face conveyors (Joughin, 1976).
[100] 1 MPa = 145 pounds per square inch (psi). An automobile tire is between 0.18 MPa and 0.25 MPa.
[101] See Whillier (1975), Clement (1975), and Marshall (1975).
[102] 1,000 kPa = 1 MPa.

translate into greater economy of drill steel with hydraulic technology. Lastly, the hydraulic drills generate lower mechanical noise and much less exhaust noise than pneumatic drills making the work environment less hazardous to the drillers' hearing.

However, as hydraulic technologies were generally more complicated than the more established pneumatic technologies maintenance tended to require a higher level of skills. As a developing technology, hydraulics also tended to be less reliable than pneumatics. During this stage of development, hydraulic power for the drills was provided by electric hydraulic packs. Besides being cumbersome these packs generated a significant amount of heat, which was compounded by the fact that the early hydraulic drills did not having an integrated chilled water service like its pneumatic counter parts.

While bearing those fundamentals in mind, it is important to realise that development of the hydraulic drill and hydraulic power are separate stories with complementarities. As with the drill, the first generation of EH power equipment focused on a mixture of 95% water and 5% oil (95-5). Originally, COMRO worked with the United Kingdom (U.K.) based *Vickers Systems* in developing the 95-5 hydraulic power system, but in 1978 German-based *Hammelmann* also became involved. By the early 1980s, the initial electric-hydraulic packs on the stopes had been replaced by centralized stations, which made hydraulic technologies less cumbersome and did not introduce additional heat on the stopes. However, besides the drills development of EH power equipment held promise as an alternative to electric power. Because pneumatic power could not be efficiently provided in large quantities and generated little force, other equipment on the stope like the scraper winches utilized electric power. While electric power could be provided relatively efficiently in large quantities, it generated little force and introduced additional heat on the stopes. Therefore, EH power seemingly offered an important alternative to both pneumatic and electric power underground (Joughin, 1982).

In development of the first generation 95-5 EH drill, COMRO collaborated with United States (U.S.) based *Ingersoll-Rand*. Because of the rough operating environment, EH drills were not generally seen as viable. Inevitable leaks from an EH drill would expel environmentally and economically undesirable quantities of oil into the mine environment. Therefore, viable EH drills had to have a low ratio of water, which is why COMRO embarked with *Ingersoll-Rand* on the 95-5 drill.

Internationally, South Africa was not alone in its efforts to develop a hydraulic drill. In the 1970s, Australia, the U.K. and the U.S. all had some research initiatives into development of a hydraulic drill. In the 1970s, Australian and U.S. coalmines were working on a 60% water, 40% oil (60-40) hydraulic drill. That was too high a ratio of oil for South African mining conditions as well as the fire weary British coalmines. Thus, in the mid-1970s the British Board of Coal was also investigating development of a 95-5 EH drill. Similarly, in the mid-1970s U.S. automobile manufacturers were looking at using hydraulic cutters on a large scale and needing to economize on oil losses, they began to develop an 95-5 EH system. Accordingly, South Africa through COMRO was participating in an international learning environment with a diversity of experiences to draw-on for technological development as well as expertise.

Three particularly significant challenges were met in developing a commercially viable 95-5 EH system for stoping on the Witwatersrand. First, because of the low viscosity it was necessary to introduce additional seals to prevent leakages. Those additional seals introduced additional friction, which caused all the seals to wear and deform much more rapidly. Therefore, COMRO collaboratively developed special plastic seals and bearings (Walczak, 1984).

A second challenge arose because at the 95-5 ratio the difficulties combining oil and water are no longer trivial (Wymer, 1976). The distances travelled by the low oil emulsions before reaching the drill would often cause a separation of the oil from the water i.e. a breakdown of the emulsion would occur. Eventually, a solution this problem of suspension came from U.S. oil corporations who developed micro-emulsions, which because of their much finer dispersion created a more stable mix of oil and water.[103]

Lastly, another major challenge in development of the hydraulic drill was in the mechanism to rotate the drill steel. The low-oil emulsions were causing traditional mechanism to wear at an unacceptable rate. After many iterations, a major break-through was realized when a quadruple plunger, ratchet and clutch, rotation mechanism was created.[104] By the early 1980s, *Ingersoll-Rand* and COMRO had developed two generations of prototype 95-5 EH drills as well as a production model. As they prepared for production trials COMRO also began systematic research into the necessary changes, innovations, to the labour force organisation to accommodate this new technology.[105]

With nearly a decade of diverse research behind them the 95-5 EH drills began their first production trials at West Driefontein gold mine in June 1983. Even before production trials began, significant optimism around the suite of hydraulic technologies had been building and applications beyond deep-level gold mining were envisioned. By the early 1980s, the next phase of research, development of a HH system, had also begun.

2.2 Development of water (hydro-) hydraulic technologies

By the late 1970s and early 1980s, senior managers at COMRO began to initiate researcher into HH (100% water) technologies. An intermediate step between 95-5 EH technologies and HH technologies were 98% water, 2% oil (98-2) EH technologies. At this time, under COMRO's direction, South Africa had become an international leader in these hydraulic technologies.[106] Remembering that the 1974 mechanization research programme was ending, three factors appear to be particularly significant in further development of HH technologies.

First, as previously mentioned, the revolutionary mechanical rock breaking program had found good performance in its drag-bits when used in conjunction with high pressure water, around 30MPa, on the rock surface. This performance resulted from the removal of waste rock under the teeth.[107] That research created a need for an all water high-pressure sprayer and development of that sprayer in the mid to late 1970s, gave COMRO important confidence in the feasibility of developing a HH power system.

Second, with the ever-increasing depths of mining on the Witwatersrand cooling had become critical. Previously, cooling had occurred at the surface and then the air was transported with pressure to required depth. However, the air warmed up in the process of transporting it and a significant amount of cool air escaped along the way to its final destination. Thus, gradually refrigeration units were moved underground. From 1972, COMRO undertook R&D into utilising chilled mine service water to directly cool the rock surface on the stope. With successful full scale trials between 1975 and 1977, it became clear that the direct application of chilled water on the rock surface was the best means to achieve a stable and tolerable underground temperature

[103] In this, the interest of the U.S. automotive industry in a 95-5 EH cutter may have been important.

[104] As additional drill manufacturers subsequently became involved, other rotation mechanisms proved viable.

[105] See Glassborow and Veldsman (1982) and Veldsman and Pretorius (1983).

[106] For instance, the U.S. in the early 1980s were still working out problems in development of 60-40 EH systems.

[107] See Hood (1976) and Joughin (1978) for details.

at increasing depths.[108] A fundamental efficiency of HH power thereby emerged, since it could function as both a cooling technology without the ad hoc difficulties of water-cooling with compressed air and simultaneous power source. Therefore, in 1980, COMRO initiated research into combined hydraulic power and cooling systems.

Lastly, with increasing depths of the gold mines' operations the latent energy in the column of mine service water was appreciated. A two kilometre column of water has a pressure of 20 MPa, which is the pressure needed to power the hydraulic drills. In hindsight, this resource was obvious. Water had to be pumped out of the mines anyway and since energy recovery turbines were already being utilised to pump water out of the mines, tapping into this system only required further development of sub-systems to keep the water in the pipes and move it to the rock face.

Therefore, in addition to the comparative drilling efficiencies of hydraulic drills over their pneumatic counterparts, HH power held systemic benefits for underground operations. Given this priority for hydraulic power, COMRO established an independent hydraulic power project and moved quickly toward development of HH power systems. By 1983, a prototype 98-2 EH power system had been developed and in 1984 it was tested at the number three shaft at Kloof gold mine (Joughin, 1986). Further development led to a prototype HH power system in 1985, which was also tested at Kloof along with ancillary HH equipment like scrapper winches and roof supports (Brown et al. 1986).

In the mid-1980s, South African based *Crown Chrome Platting* also became involved in HH power technologies while *Vickers Systems* withdrew from the research initiative. By the mid-1980s HH power had broadly proven its viability and awaited complementary development of ancillary equipment before it could be considered part of a truly commercially viable technology system. In 1988, COMRO began working with equipment manufacturers to develop an integrated open system with chilled water.[109] Because of the high pressures and associated dangers, technologies from the oil and nuclear industries were borrowed to guide development of HH piping systems. Safety systems from the nuclear industry were given particular attention because of their necessity for a rapid shut-down in case of failure.

In contrast to HH power systems, whose relative complexity reduced with the removal of oil, the complexity of HH drills increased. Nonetheless, as COMRO embarked on 98-2 EH drills on the way to HH drills, they were no longer in sole partnership with *Ingersoll-Rand* as the South African-based *Seco* and *Novatek* also joined the research initiative. Moving to the 98-2 drill was relatively straight forward, since the new emulsion mix, bearing and seal technologies transferred relatively easily from the 95-5 drill. Thus, in 1986 production trials of the 98-2 drill began on Anglo-American Corporations' (AAC) Orange Free State mines and on Gold Filed South Africa's (GFSA) Far West Rand mines.[110] After these trials in 1987, COMRO withdrew from further research in EH drills, concentrating on HH drills and leaving further development of EH drills to the equipment manufacturers. Nevertheless, by 1989 several production model 98-2 EH drills were available when Switzerland based *Sulzer* joined COMRO's initiative to develop a HH drill.

It is worth briefly describing the development of EH and HH technologies by the additional firms. *Seco*'s entry into the research initiative was highly significant since they dominated production of pneumatic drills sold in South Africa at that time. Seco took one of their oil hydraulic rock drills and converted it to a run on a 60-40 EH mixture.[111] Gradually they dropped the level of emulsion in the drill until it had was running as a HH drill. Despite good results in the laboratory the drill did not perform

[108] See Wagner and Joughin (1989) for details.
[109] See Brown and Joughin (1988) and Du Plessis and Soloman (1988) for details.
[110] See Westcott (1986), Holloway et al. (1987), and Du Plessis et al. (1989) for details.
[111] That drill was known as the HD-30.

well in operation trials. Hence, as other companies released more reliable HH drills, Seco shifted further development of an HH drill to its U.K. facilities before eventually abandoning the project. *Novatek* was established expressly as a technology development company to participate in COMRO's hydraulic technologies programme. While a sister firm, *Innovatek* had been subsequently established to manufacture its drills, demand surpassed Innovatek's capacity in the early 1990s leading to a merger with U.K. based Gullick in 1992. Sulzer, in contrast to the other companies, developed its drills in Switzerland although in close collaboration with South Africans. Sulzer's first drill was based on the company's turbine pump technology.[112] However, after initial prototypes were developed production of Sulzer's drill was based in South Africa were further development of the drill also occurred.

Several additional challenges emerged as COMRO shepherded the initiative past 98-2 EH drills and on to HH drills. One fundamental challenge was around lubrication. Boundary lubrication prevents wear of two surfaces in contact. Even just atomic quantities of oil are sufficient to form a hydrodynamic film of fluid that would lubricate contact surfaces. However, in HH systems they found that boundary lubrication was not occurring. Thus, a range of solid lubricants like polymers, rubber and non-steel materials were investigated. Rubber was the eventually solution for static seals while polymers were utilised for dynamic seals. For bearings, polymers were the only viable materials.[113]

Another major challenge was the corrosion of steel because of its contact with the highly corrosive mine water. While 98-2 EH systems were sufficient to prevent corrosion, the pure water of the mines' was too harsh for the normal steel. Because existing alternative corrosion resistant material broke down under the mechanical forces that the drill were subjected, COMRO initiated development of novel corrosion resistant steels. These hybrid steels were developed in collaboration with U.S. and U.K. steel manufacturers. Despite good results from pilot melts, in the end they adapted existing steel. In fact, while the problem was particularly severe for the drills corrosion was also a concern in the other equipment as well as the piping and power systems themselves.[114]

Progress in the HH drill was made continuously through the late-1980s, even as COMRO's organisational future was in doubt and *Ingersoll-Rand* withdrew from the research initiative.[115] Thus, in the early 1990s when GFSA announced its commitment to an entirely HH system in its newly developed Northam Platinum mine an important impetuous was created for the final drive in developing HH technologies. HH technologies were particularly appealing for Northam platinum mine because of its high underground temperature gradient.[116] While HH mining systems were still being developed, the technology was being deployed at Northam. Nevertheless, HH technology proved itself commercially viable through its deployment at Northam and by 1991 *Ingersoll-Rand*, *Novatek* and *Sulzer* each had production model HH drills (Solomon and Jones, 1994).

South African HH technologies for mining drew on international precedents in developing a unique technology. Under COMRO's stewardship important complementary international technologies were brought into the programme that eventually enabled viable HH technologies to be established. Representing the mining-finance group's demand COMRO interacted directly with a spectrum of research,

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112 This drill was known as the Turbo Drill.

113 See Harper (1990).

114 See Howarth (1990).

115 See Section Three for details.

116 At a depth of two kilometers mines on the Witwatersrand were usually faced with an underground temperature of 32º C at Northam at two kilometres the underground temperature was 65º C.

development and equipment manufacturers in facilitating the emergence and commercial supply of an important alternative technology for stoping on South Africa's deep level gold mines.[117]

By the early 1990s, a commercially viable HH technology existed. In the early EH phases of its development fundamental drilling economies supported development of power systems, while efficiencies in the power systems assisted development of drills. While these mutual forces were important throughout, in the HH phases systemic efficiencies associated with the necessity to cool increasingly deep and hot mining environments as well as the static energy held in the column mine service water added significant optimism to the eventual diffusion and impact of HH technology.

However, the technical promise of HH technology has not been followed by the large uptake originally expected.[118] Currently, there are only four mines in the world that operate open HH systems and these were all involved in COMRO's development of the technology.[119] Among prominent reasons for the limited diffusion of HH technologies are differences between technical and operation efficiencies, the nature of the ore bodies that HH systems are designed, and inherent technological complexities.

Because there is no oil in HH equipment it must be manufactured to much greater degree of precision the oil hydraulic or EH equipment.[120] That greater precision adds a fundamentally higher level of complexity and cost to the manufacture of HH equipment compared to other equipment. This inherent cost could be offset by production efficiencies and health and environmental savings,[121] but presently those benefits are not sufficient to induce the conversion of established mines to HH systems.

Another factor impeding the uptake of HH systems is that they are designed for relatively deep-level tabular ore bodies. The advantages of an HH system are greatest if it is part of the initial design of a mine. Presently, there is not much development of relatively deep-level mines because of the longer time necessary to realise a return on investment. As a result HH technologies must compete on a basis of ad hoc advantages over other established systems. In additions, the HH system was designed for mining Witwatersrand gold deposits which exist in the presence of a lot of mine service water. Few other ore bodies are reported to use nearly as much mine service water in their operations, which also reduces some of the inherent benefits of HH systems.

Lastly, underlying differences between technical and operating efficiencies have combined with the other factors to inhibit the diffusion of HH technologies. These differences between technical and operating efficiencies exist for several reasons. One issue is path dependence in the existing pneumatic-based system of stoping which creates agglomeration and routinization economies.[122] As long as pneumatic technologies predominate training and maintenance of personnel to utilise those

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[117] Notably international intellectual property rights did not play a significant issue in the development of HH technologies nor did foreign technology inflows enhance the incentives for innovation or diminish them.

[118] See Paraszczak et al. (1994), Wyllie (1990), and Joughin (1984) for examples.

[119] These are GFSA's Kloof and Beatrix Gold Mines, AAC's Tau Lekoa Gold Mine and Northam's Northam Platinum Mine.

[120] Acceptable precision in HH equipment is reportedly around +/- one micron (a millionth of a meter) compared to +/- twenty microns in oil hydraulic equipment.

[121] Among the more important environmental benefits of HH technologies are their removal of oil from the working and maintenance environment. In addition, HH drills have lower over-all noise than even muffled pneumatic drills which reduces worker hearing damage.

[122] See Arthur (1994) and David (1985) for further information on the concept of path-dependency.

technologies is common good. In contrast, similar economies can only be realised if a critical number of producers adopt HH technologies. To the extent that these economies exist, the concentration of mining activities acts to inhibit rather than facilitate technological progress. Some industry analysts have suggested that a limited absorptive capacity with the mining-finance groups themselves has also hindered the diffusion of HH technologies. When HH technologies were developed the engineering skills available were reported to be much higher than they are today. As a result, many mines do not have the requisite engineering capacity to divert from established operational practices or organisational routines.[123] Inter-agent authority over production also appears to be another important feature in the limited diffusion of HH technologies. In this respect, productive efficiencies from the introduction of HH systems on the stopes represent a potential reduction in the stoping workforce. Consequently, labour unions representing these workers have expressed resistance to the introduction of HH technologies.

3 Aspects of mining's system of innovation[124]

Development of the hydraulic technologies described in section two depended fundamentally on COMRO. As a co-operative research organisation COMRO reflected interests of the South African mining industry, particularly the mining-finance groups and the Witwatersrand gold mines, but these interests were distinctly translated through COMRO's organisational culture. This section analyzes the institutional architecture in which hydraulic technologies were developed. Therefore, its central focus is on what gave rise to the formation of COMRO, how did COMRO evolve, why did COMRO dissolve, and what was the dynamic relationship between COMRO and hydraulic technologies. Since COMRO was part of COMSA, it is worthwhile to briefly review the role played by COMSA in the mining sector's system of innovation before COMRO.

From its earliest days COMSA engaged in the shaping of science and technology (S&T) policy. One of the most important and enduring means that COMSA did [does] this is through its Patents Committee. Established in 1892, the Patent Committee's original purpose was to contest the patent of the cyanide-based gold extraction process.[125] Besides settling the cyanide process patent, the Patent Committee took on a much broader role of surveying the granting of intellectual property rights in South Africa in order to ensure patents were not granted to public technologies.

Early on COMSA also attempted to co-ordinate the R&D of technologies for the industry. Thus, in 1893 it established a Metallurgical Sub-Committee to support the commercial development of cyanide based extraction technologies.[126] Then in 1908 COMSA established a Mine Trials Committee to facilitate development of pneumatic rock drill for stoping. Before COMRO, perhaps the most important step that COMSA took in the coordination of technologies for the industry was its

[123] See Chapter Five in Nelson and Winter (1982) for an elaboration of the economics of organisational routines.

[124] This section benefited from discussions with George Ashworth, George Harper, Noel Joughin, Alex du Plessis, John Stewart, and Denis Wymer. However this section is not, necessarily, a reflection of their opinions and inaccuracies that might exist are the authors'.

[125] Cyanide-based extraction was critical to economically mine the vast majority of the Witwatersrand's gold deposits. Hence, in the face of a hostile Afrikaner government, the mining-finance groups undertook a role in ensuring intellectual property rights were not applied to public knowledge that would usually have been left to the patent office itself.

[126] Strictly speaking, the Metallurgical Sub-Committee was acting to facilitate development of a viable metallurgical process to extract gold from the pyritic deposits.

establishment of the Technical Advisory Committee (TAC) in 1922 and the independent position of Technical Advisor (TA) in 1923.

Table 14 - Select dates in the history of the mining sector's system of innovation (1896-1992)

1892	COMSA establishes Patent Committee
1893	COMSA establishes Metallurgical Sub-Committee
1908	COMSA establishes Mine Trials Committee
1914	COMSA establishes Dust Laboratory, based at COMSA head office
1922	COMSA establishes Technical Advisory Committee (TAC)
1923	Independent post of COMSA Technical Advisor (TA) established
1937	COMSA establishes Timber Research Laboratory, based at COMAS head office
1947	TAC raises need for separate labs for Dust and Timber laboratories - new facilities opened 1951
1953	COMSA conducts rock burst research previously done by Mining-Finance Groups and CSIR
1954	COMSA establishes Applied Physiology Laboratory at Crown Mines
1957	COMSA TA, M. Falcon, begins search for director of COMSA research
1960	COMSA establishes Research Advisory Committee (RAC)
1961	COMSA commissioned Schonland Report recommends establishing post of research advisor
1962	William Rapson becomes first COMSA Research Advisor (RA)
1964	Rapson unites research focuses of COMSA under single organization, COMRO
1971	U.S. Dollar convertibility to gold ended
1974	Malawi suspends COMSA labour recruitment
1974	COMSA commissions restructured COMRO on large-scale 10 year mechanisation research initiative
1988	COMRO review of delivery to industry leads to increased consulting emphasis
1989	COMRO budget cut significantly, COMRO tasked to co-ordinate mining research
1990	Further COMRO budget cuts lead to changing scope and structure, with safety research separated
1990	RAC and TAC merged to form Technical and Research Advisory Committee
1991	SIMRAC created, effected from 1993
1992	Merger of COMRO with CSIR finalised, effected in 1993

Source: Compiled by authors

The TAC was formed in the midst of a difficult transition of stoping practices on the Witwatersrand gold mines. The TAC consisted of one consultant and one mine manager from each of the seven principle mining-finance groups that operated on the Witwatersrand. Initially, the TAC was tasked with advising on issues forward to it by the Gold Producers Committee (GPC). However, with its establishment of an independent position of TA, the TAC was allowed to initiate investigations around technical issues that it identified as being important for the industry. While broadly concerned with new technologies that might be applicable to the industry and thereby R&D into those technologies, the TAC was first and foremost a committee of engineers focused upon the application of new technologies in the industry.

Before COMRO, COMSA also had established several research laboratories. In 1914, it established the Dust Laboratory. Based at COMSA's head offices in downtown Johannesburg, the Dust Laboratory tested the quality of air underground. Then in 1937, COMSA established a Timber Research Laboratory, also based at COMSA's head quarters, to develop treatments to make wooden stope supports more resistant to decay. Housing these research laboratories at its administrative headquarters was not an ideal situation and in 1947 the TAC initiated development of separate facilities for these laboratories in a neighbouring suburb of Melville. The Melville facilities opened in 1951. A few years later in 1954, COMSA established an Applied Physiology Laboratory at Crown Mines in order to conduct research in the physiology of working in the hot and humid underground environment of the mines. Around the same time, COMRO also replaced a consortium of mining-finance groups in collaborative research initiative into underground rock burst with the Council for Industrial and Scientific Research (CSIR).

Thus, in the late 1950s COMSA took an increasingly active role in R&D. To a certain extent this role was handed to COMSA as a result of the withdrawal of Rand Mines from South African mining operations.[127] Rand Mines had from the early days of Witwatersrand gold mining been a leading innovator with a policy of diffusing these practices to the other mining-finance houses. Rand Mines' withdrawal from this role of leadership in the industry's system of innovation therefore represented an important loss. While other mining-finance groups had quality internal R&D capacity, they were not apparently willing to replace Rand Mines as the industry's leader in innovations. COMSA was naturally positioned to act as a leading coordinator for the future productive innovations, but this was not true organisationally. Development of that organisational capacity would lead to the establishment of a Research Advisory Committee, an independent Research Advisor and eventually COMRO.

In 1957, the Technical Advisor to COMSA, Michael Falcon, began a search for someone to director the disparate COMSA research laboratories. That search led Falcon to the U.K. where he contacted Sir Basil Schonland, a leading South African expatriate scientist and science advisor.[128] Falcon's 1957 search for a director did not produce a suitable candidate, but it did initiate a dialogue with Schonland about the future of research within COMSA. An important issue thereby identified was the predominant engineering culture within COMSA. Schonland appears to have advocated COMSA's development of a science management capacity if COMSA was going to have an enhanced role in co-ordinating the development of new technologies for the industry.[129]

A first step towards COMSA taking up the gauntlet of industry research came in 1960 when the Research Advisory Committee (RAC) was formed. The RAC was tasked with the organisation, direction and control of all research conducted by COMSA (Findlay (1960). Operationally, the RAC reviewed all proposed research projects from COMSA members to determine if they warranted an industry-wide research initiative. Suitable projects were then referred to a steering committee to establish costs before RAC sent the proposal to the TAC. The TAC then forwarded the RAC's proposals to the GPC for budget authorisation. Throughout the projects' life the RAC was responsible for monitoring and evaluation upon which it reported to the TAC. Before establishment of the RAC, there was only a piece-meal reporting structure by the COMSA laboratories to the TAC.

Although the RAC facilitate a certain degree of research co-ordination within COMSA the various laboratories continued to operate independently. Realising that further changes were necessary, in 1961 COMSA invited Schonland to formally review all aspects of research currently being conducted by the industry and to make recommendation. Schonland's report highlighted the need within the industry to make research a career enhancing option for individuals with postgraduate qualifications (Austin, 2001, p. 589). His report called for the appointment of a scientific advisor to COMSA. Acting on Schonland's review, COMSA established the post of Research Advisor[130] and the position was filled by William Rapson in 1962.

[127] See Cartwright (1968) for details.
[128] See Austin (2001) for a biography of Schonland.
[129] There has been a long historic divide between scientist and engineers, which although it perhaps not as evident today it has played a significant role in shaping their respective disciplines. See National Academy of Sciences (1985).
[130] According to Austin (2001) the post of Research Advisor was chosen instead of Science Advisor to assuage any ill-feelings the engineers might have toward scientists.

Rapson immediately began to promote an organisational integration of COMSA's various research laboratories as a first step to a more coordinated and larger role for COMSA in the industry's system of innovation. These efforts eventually led to the establishment of COMRO in 1964 with Rapson, as the Research Advisor, its Director (Lang, 1990, p. 114). COMRO gradually established its role in industrial research under Rapson. Particularly important in this regard was the previously mentioned1965 establishment of the Mining Research Division, which undertook research into underground equipment and began investigating alternative methods of mining.

1974 marked an important year in the development of COMRO's research activities. First, Salamon succeeded Rapson as RA. Second, Rand Mines' research laboratories in Melville, near COMRO's 1951 facilities, were taken over by COMRO. Lastly, the industry supported COMRO's initiation of a large ten year research programme into mechanisation.

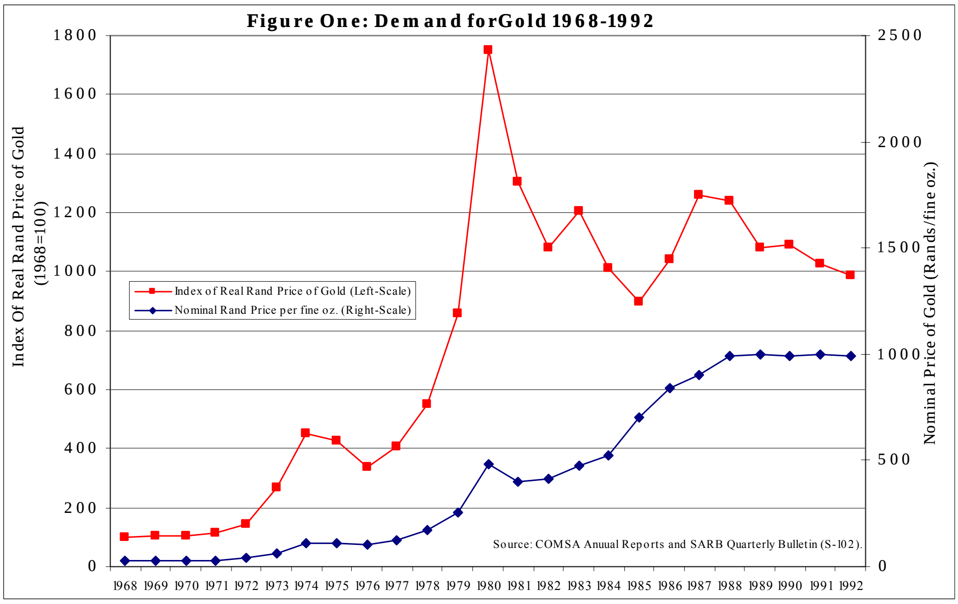
While the relevance of the 1974 research programme has already been discussed at length, it is important to reiterate some features. The need for the mechanisation programme originated from the increasing depth of gold mining and the racial occupational mobility restrictions of operations. Salamon restructured COMRO in alignment with the mechanisation focus, importantly then given the scale of the programme, COMRO became research into mechanisation.

When the ten-year mechanisation programme was finished, the contextual environment that had originally supported it had significantly changed. The mining-finance groups began to position themselves within a broader environment of international operations. Increasingly, research and organisational know-how played an important role in their competitiveness and as such the role for a co-operative research organisation was circumscribed. In fact, the beginnings of the changing borders of gold mining cooperation was signalled in late-1970s when the mining-finance groups ended collaborative funding of mine hospitals in the OFS. A further signal then came in 1985 when collaborative funding other mine medical facilities was withdrawn. Within the Witwatersrand gold industry this transformation became apparent in the increasing decentralisation of mining activities. In the 1980s standard systems employed across all mines in mining-finance group began to be replaced by greater customisation to account for the variety of conditions.

With the end of the ten-year mechanization programme COMRO continued a large research agenda after an organisational restructuring in 1985. The gold industry's enthusiasm for the co-operative research initiative was waning. In 1988, the GPC advised COMRO to increase it consulting activities following a review of its services to industry. Then in 1989, COMRO's budget was significantly reduced and its organisational objectives were redefined as being to co-ordinate industry research.

Around the late 1980s the Government Mine Engineer saw the withdrawal from COMRO by industry with concern because of its associated reduction in safety research. State mandated safety research quickly thereby became a near certainty and thereby COMRO's transformation from a systemic co-operative research organisation was clearly on the cards. State mandated research implied a research levy on industry, which being over and above what industry was already paying for COMRO was an effective death warrant for COMRO. Thus, in 1990 following further budgetary cuts and reductions to its mission, safety research programmes were separated from COMRO's other activities. The scale of these reductions is reflected in the fact that between the late-1980s to the mid-1990s COMRO staff decreased from over 650 to 200.

Figure 15 - Demand for gold



As the gold industry withdrew support from COMRO and COMSA,[131] the deterioration of gold demand was often cited. Figure 15 shows the real and nominal price of gold between 1968 and 1991. From 1984 to 1991 the average real annual compound price of gold in rose at a sluggish 0.2%. Perhaps, more importantly given the general restructuring that was occurring anyway, the average real annual compound price of gold between 1987 and 1991 decreased by 5.2%.

In the 1980s, as the industry began to transform increasing discord emerged between the GPC, the TAC, and COMRO. The TAC was historically a powerful committee, but gradually it grew distant from the GPC and by the late-1980s its power had been internally weakened in response. Thus, in 1990 the RAC and TAC were merged into a weaker Technical and Research Advisory Committee (TRAC).

With COMRO's demise eminent, Alan Munro from GFSA began steering COMRO's merger into the CSIR, upon which he sat as an Executive Board member. This led to a three to four year window in which elective cost sharing by the industry was closed out and COMRO focused on contract based research within the CSIR. Realizing the important role of mine safety research, COMRO actively sought to inform the structure of State mandated mine safety research. Thus, when SIMRAC was effected in 1993 with the Minerals Act, COMRO, or the CSIR's Mining Technology Division (CSIR-Miningtek) as it was then called, was well positioned as a preferred service provider to SIMRAC.

COMRO functioned as R&D management specialists with vested interest in the needs of the industry. It formulated broad, encompassing, technology strategies and limited nurturing its own capability to areas where expertise did not exist or was not available locally. While CSIR-Miningtek has continued to occupy COMRO's facilities it is a much different research organisation than its predecessor. Notably CSIR-Miningtek no longer undertakes comprehensive management of a research project like COMRO did with hydraulic technology. COMRO played facilitating role in research through its publication of research reports that were circulated to all members of COMSA.

[131] Concurrently, COMSA's mission as industry association radically transformed. This is reflected in COMSA staff decreasing from 6,800 in the late 1980s to 70 in 2001.

Complementary to this release was the diffusion of knowledge through professional societies like the Association of Mine Managers. COMRO had its short-comings, in particular it had a very rigid organisational structure coupled to a linear approach to innovation.

While many individuals and firms made major contributions to the development of HH technologies, without COMRO it is doubtful that an integrated HH system would ever have been developed. However, the highly hierarchical internal structure of COMRO led to some to view it as being driven by internal dynamics rather than the needs of its co-operative patrons, the South African mining-finance groups. COMRO emerged as a major player in the mining sector's system of innovation in a period when South African mining-finance groups were under pressure from international isolation. Thus, a certain degree of domestic insularity apparently co-existed with relatively extensive international research relationships.

Concurrent with the increased internationalisation of the South African economy since independence and the associated international diversification by South African mining-finance groups,[132] the mining sector experienced an international decrease in public research.[133] The dissolution of COMRO has left a gap in the systemic co-ordination of research and development in sector's system of innovation. Thus, South Africa at present has a fractured system of innovation in mining that is structurally unlikely to be capable of developing a similar system of inter-connected technologies.

4 Evolution of HH technologies[134]

This case is part of a project centrally concerned with the 'lateral migration' of technologies. The concept of 'lateral migration' has been discussed elsewhere and the authors' interpretation is briefly reviewed at the beginning of Section 4.2 below. Before turning to an analysis of the lateral migration of HH technologies it is important to describe the evolution of the original market for HH technologies. Therefore, Section 4.1 reviews the contemporary market structure for HH technologies in mining. Complementing our understanding of the evolution of HH technologies since the conclusion of the COMRO initiative, Section 4.2 examines applications of HH technologies in markets outside the mining sector. Section 4.2 there by describes actual and emerging markets for the lateral migration of HH technologies. In its entirety this Section gives one an indication of the comparative scale of markets for the 'lateral migration' of South African HH technologies from their origins in the mining sector.

4.1 Evolution of the original market for HH technologies

Geological characteristics within and particularly between mines require a significant degree of technological adaptation if a productive system is to operate efficiently. When different commodities are being mined an even greater degree of adaptation is necessary. Hence, when HH technologies are introduced they are not simply

[132] Notably, the international diversification of South African mining-finance groups was also associated with a decrease in intra-industry ties that has decreased the scope for intra-industry cooperation.

[133] Among other international examples was the 1996 closure of the United States Bureau of Mines.

[134] This section benefited from discussions with Peter Fraser, Frank von Glehn, Bill Gore, George Harper, Peter Hes, Geoff Minnitt, Alex du Plessis, Mike O'Conner, and Julian Wills. However this section is not, necessarily, a reflection of their opinions and inaccuracies that might exist are the authors'.

unpackaged and plugged in. Experiences with the introduction of HH technologies therefore are also intertwined with fundamental features of the ore deposits themselves. This incestuous nature is further reinforced in the case of HH technologies by the fact that only four mines, three South African gold mines and one South African platinum mine,[135] have adopted an open HH system. While some HH technologies are used in other mines across South Africa and internationally, these four mines remain the core source of demand for HH technologies in the mining sector. Thus, in discussing the evolution of the mining sector's demand for HH technologies this section focuses on that demand and the experience of the companies supplying HH technologies to that market.

In the conclusion of Section Two several reasons for the relatively limited adoption of HH technologies were discussed. These included inherent technological complexities, the specific nature of the ore bodies for which HH systems were designed and resistance because of technological path dependency. Notably, the four mines that have adopted open HH systems were all involved in the original COMRO project. The fact that HH technologies have not been adopted on a large scale is in part a circular reason why the principal demand for the technology remains centred around these four mines. The industry standard remains established pneumatic systems since there are added costs, risks and uncertainties associated with a non-standard technology like HH systems.

Despite these barriers several niches appear to have been established for the original HH technologies. At least on the gold mines one of the most significant of these appears to be HH sprayers used to facilitate removal of blasted material from the stopes. While the HH drills have not been used extensively in stoping they have had greater success in tunnelling or development.[136] Demand for HH equipment like HH shovels, winches, and chainsaws and drill rigs has also developed. Niche applications of HH technologies typically utilise micro-HH packs to power the equipment.

Table 15 - Select dates in market development of HH technologies

1975	Ingersoll-Rand undertakes hydraulic drill development with COMRO
1975	Vickers Systems undertakes hydraulic power development with COMRO
1978	Hammelmann undertakes hydraulic power development with COMRO
1979	Gullick undertakes impact ripper development with COMRO
1982	Seco and Novatek undertake hydraulic drill development with COMRO
1985	Hydro Power Equipment (HPE) established
1987	TLC Software established
1988	Crown Chrome Plating undertakes hydraulic power development with COMRO
1989	Ingersoll-Rand ends hydraulic drill development with COMRO
1989	Sulzer undertakes hydraulic drill development with COMRO
1990	Turgis Consulting established
1991	Northam Platinum mine commissioned on HH technologies
1992	Joules Technology established
1996	Sulzer begins producing New Generation Drill for HH technologies
2003	Sulzer begins development of HH-Air Rock Drill

Source: Compiled by authors

Prospects for the future diffusion of HH technologies retain a strong potential, despite the slow growth in demand so far. A primary reason for this optimism is that HH technologies remove polluting oil from operations. To date, the costs of HH technologies are still largely prohibitive in comparison to traditional oil hydraulic or EH technologies. Rising concerns with negative environmental externalities associated

[135] See Footnote 39 for a list of these four mines.

[136] Reportedly this greater uptake is associated with lower workforce resistance to HH technologies in these activities.

with oil-based technologies are therefore a fundamental source for optimism around the broader potential for HH technologies diffusion in the mining sector.

One equipment supplier, Sulzer, has taken a proactive role and sought to facilitate the introduction of HH technologies within the existing standard practices and organisational routines that exist in mining. This approach led them to develop a new generation of HH technology in their Aya Duma Duma drill, which is a HH lubricated pneumatic drill. Sulzer has thereby developed a drill that works on the pneumatic infrastructure existing in most mines, but that also introduces productive and most importantly environmental benefits associated with HH technologies.

Important dates in the development of the market for HH technologies are listed above in table 15. With a broad view of the productive system it is not surprising that besides equipment manufacturing there are a host of complementary services and firms providing services associated with the supply of HH technology. Given the limited number of firms associated with supplying HH technologies to the mining sector, these firms and their involvement with HH technologies is reviewed below. Services provided by equipment manufacturers are discussed in turn before turning to a review of specialist service firms associated to HH technologies.

- *Crown Chrome Plating* – Having been involved with the development of pumps for HH technologies with COMRO, *Crown Chrome Plating* continues to manufacture micro-HH packs for HH technologies under its Cemo Pumps subsidiary. These packs are driven by a positive displacement pump that is also sold to the construction, food processing, manufacturing, and agriculture sectors in applications ranging from milk processing to plastering and injection mortar.
- *Hydro Power Equipment (HPE)* – Emerging in the mid-1980s around the COMRO HH research initiative, *HPE* is now a leading firm supplying hydro power systems and equipment. Among the equipment supplied by HPE are HH rock shovels, compressors for loading explosives, saws for roof support timbers, drill rigs, and in stope water jets. *HPE*'s hydro power systems include high pressure couplings, reticulation systems, valving, roof support props, drill rigs, high-pressure control and safety systems, and turbines. In terms of complementary services, *HPE* actively fosters development of knowledge and expertise in HH technology. This includes running training courses in the utilization and maintenance of their HH equipment as well as providing a dedicated service engineers on-site for their larger customers.
- *Ingersoll-Rand* – Despite their leading role in development of the HH drill by the late 1980s and early 1990s *Ingersoll-Rand* was withdrawing resources from further development of HH drills. Nonetheless, Ingersoll-Rand produced a commercial HH drill. Rights to manufacture that drill were purchased by *Joules Technology* in 1999 who continued its manufacture until 2002 when demand for this relatively dated technology led *Joules* to discontinue manufacturing.
- *Joules Technology* – Established in 1992, *Joules Technology* became an important supplier of HH based cooling and ventilation equipment. In addition to the licensed manufacture of *Ingersoll-Rand*'s HH drill mentioned above, *Joules Technology* produces a range of HH other equipment including HH winches, chainsaws, and in stope water jets. In terms of complementary services, *Joules Technology* provides on-site workshops for its larger customers.
- *Novatek* – Emerged in the early 1980s as an organisation focused on development of an HH drill under COMRO's stewardship. In the early 1990s it merged with U.K.-based *Gullick* whose background in the U.K. coal industry had led to their involvement with COMRO's HH programme in the late 1970s. In the mid-1990s a management buy-out led to Novatek again being an independent, South African based, HH drill manufacturer. In partnership with its sister company *Nestek*,

Novatek offers a small HH drill that runs on either a high-pressure system or a low-pressure system. In terms of complementary services, *Novatek* offers HH drill maintenance contracts in conjunction with several on-site workshops as well as hosting a training department that provides class-room and on-the-job training in stoping with their HH drill.

- *Seco* – Despite its historic pre-eminence in supplying pneumatic rock drills for the South African mining industry, in the early 1990s *Seco* analyzed the potential demand for HH drills and perceiving it to be a niche technology ended its research efforts in the development of an HH drill, which had been transferred to their U.K. facilities.
- *Sulzer* – Entering into COMRO's HH programme in the late 1980s with its turbine technology its development of the lighter-weight New Generation Drill based on a South African design expanded its HH product demand in the mid-1990s. As mentioned above, since the early 2000s *Sulzer* has taken an important initiative in HH technology in its development of the HH lubricated pneumatic drill.

A few firms in the service sector also had ties to COMRO's HH programme. In contrast to the HH equipment suppliers most of these firms now find HH technologies to play an ancillary role in their businesses. One of the more prominent examples of this class of firm is the mining consultancy *Turgis*. It was founded in 1990 by several COMRO staff members that were heavily involved in the HH programme. Despite its staff's knowledge of HH technologies still forming a core competency, *Turgis* has found demand for other mining consultancy services to greatly surpass demand for its knowledge of HH technologies.

Another service firm that emerged from COMRO's HH programme was *TLC Software*. It was established by three COMRO employees (Terry, Louis and Chris) who had designed the software, instrumentation and measurement system for the HH system. Today, *TLC Software* offers a range of specialist engineering software solutions. Similarly, *BBE* a mining consultancy specialising in cooling and ventilation had some staff that worked on the COMRO HH programme. This knowledge of HH technologies continues to play a minor role in BBE's business, but the vast majority of its operations are focused on other mine cooling and ventilation technologies.

In terms of HH technology for the mining sector, South Africa is an international leader. The niche role played by HH technologies in mining activities both in South Africa and internationally has insulated these capabilities from strong international competition. Potential application of this technology on a much greater scale in the mining sector persists, but to date demand has remained relatively static.

4.2 Lateral migration of HH technologies

With this project's focus on 'lateral migration' we are focusing on evidence of technology's application in a distinct sector and context from that which it was originally developed. Even though the legacy of HH technologies described in Section 4.1 included the emergence of HH technologies within the service sector, that migration was inter-related to HH technologies' application in the mining sector and therefore is not a case of lateral migration. These applications are briefly discussed below before turning to a review of international applications of HH technologies outside of the mining sector. The potential for the South African HH technology to grow through its deployment in these applications then concludes this section.

The clearest evidence of lateral migration for South African HH technologies is found in *HPE*'s development of equipment for the steel industry. Owing to the hazards of having oil in the working environment around steel manufacture HH technologies are logical means to move heavy equipment. *HPE* has therefore developed HH de-scalars and tap hole 'mud gun' plugger for arc furnaces. The HH de-scalar is used to clean the inside of a furnace while the tap hole mud gun is stops the flow of materials from an arc furnace's tap hole by pumping clay into its tap hole. The high pressure HH mud gun can rapidly inject a large quantity of stiff mud to safely and effectively seal the furnace. While this equipment accounts for a minority of *HPE*'s business it is a clear example of lateral migration.

Besides *HPE*'s equipment for the steel industry this analysis has not been able to find evidence of other significant lateral migration of the South African HH technologies developed under COMRO's stewardship.[137] Nonetheless, there are a host of areas where HH technologies have been applied internationally. Denmark-based *Danfoss* is one of the leading HH technology firms internationally outside of the mining sector. Its *Danfoss Nessie* subsidiary has developed HH technologies for a range of sectors since the late 1980s.[138]

On oilrigs, *Danfoss Nessie* has developed HH pumps for energy generation, these HH pumps are also being used to increase the energy efficiency of water desalination. In wood processing, *Danfoss Nessie* has developed water lubrication and cooling of saw blades to reduce friction from the wood's resin. That reduction in friction has increased productivity and lowered energy costs. Additionally, *Danfoss Nessie* has developed a range of HH heavy equipment to replace polluting oil hydraulics and EH equipment. That HH heavy equipment, such as a HH lifting garbage truck, has been adopted by municipalities in Europe who are increasingly concerned with the environmental effects of oil hydraulic leakages.

While South African HH technologies have not so far migrated into these alternate applications, their origins in the rough underground working environments of the mines has led to their developing more robust HH technologies than their international counterparts. In this regard *Sulzer*'s development of the HH lubricated pneumatic rock-drill appears to hold tremendous promise for lateral migration to other sectors. If the Aya Duma Duma drill can show its commercial viability in replacing pneumatic drills on the mines, it would have a strong base to further develop similar HH lubricated equipment for the construction and manufacturing industry. Thus, the potential for lateral migration of South African HH technologies remains highly significant even if unrealised.

5 Conclusion

South African HH technologies were developed over more than two decades under the comprehensive direction of COMRO. They have established a viable market niche in the mining sector. Despite what many believe to be a long-term boom in the resource sector the HH technologies have not diffused significantly from their original applications. There is clearly a potential for these technologies to move further out into the mining sector and a variety of other sectors as environmental externalities become an increasing concern. However, the slow diffusion of HH technologies thus far is clearly an area of concern.

While there has also been lateral migration of South African HH technologies these have been small in comparison to the demand from the mining sector. International experience has demonstrated a large variety of applications for HH technologies that

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[137] It is possible that Crown Chrome Plating/Cemo's positive displacement pump is linked to the COMRO HH programme, but so far it has not been possible to meet with a representative.

[138] For more information on Danfoss Nessie and its various applications see: www.nessie.danfoss.com

also hold a tremendous potential for further lateral migration of South African HH technologies. Bearing this history and subsequent evolution of HH technologies in mind, the remainder of this paper turns to a discussion of the four principal dimensions of lateral migration from the present projects conceptual framework.[139]

5.1 Absorptive capacity

The HH technologies described in this case originated within a collaborative initiative supported by the South African gold mining industry that was trying to increase the mechanisation of stoping operations. These efforts for mechanisation emerged from internal competitive imperatives as well as successful local and international precedents in coal mining mechanisation. COMRO, the industry's co-operative research organisation, played a major role initiating the research and directing its development to the point of commercial viability.

HH technologies are comparatively more skill intensive than the precursors they were designed to replace. This is partly because of inherent complexities in HH technologies, but the skill intensity of the technologies are also relatively elevated because routines, standards, and organisational practises in the established competing technologies have significantly reduced the requisite skills. Interviews with individuals active in the industry have indicated that changes in the organisational structure of the industry have also enhanced this barrier to HH technologies' diffusion as fewer engineering skills on mines reduce their capacity to experiment with alternative operational practices.

While international precedents were important in the initial stages of the initiative, unique features of the working environment led to the technology developing quite independently of other initiatives. In particular, the open HH system connecting stoping equipment with the latent power and cooling capacity in the South African mines created a one of a kind technology. Despite originating within the mining sector an important characteristic of the research initiative was to foster development of domestic manufacturing capacity. While specifically targeting development of manufacturing capacity for the mining industry that level of inter-industry development and common goods illustrates the high level of social capital that existed within South Africa's economy before liberation. Under COMRO's direction South African universities were also drawn into the programme where possible to develop and sustain tertiary capacities that would support HH technology as well as the broader sectoral system of innovation.

As with diffusion in the mining sector itself, applications outside of the mining sector appear to have a lot more potential scope than has been realized so far. The principal lateral migration of South African HH technologies so far has been by one firm, HPE, in their development of HH equipment for the steel industry. Among the other technologies with substantial potential for lateral migration, Sulzer's HH lubrication technology for pneumatic equipment appears to be one of the greatest. Internationally, related HH technologies are being used in a variety of sectors. Given the comparatively robust nature of the South African HH technologies this domestic capacity appears well positioned for further lateral migration.

5.2 The role of foreign technology

While deliberately fostering domestic absorptive capacities, COMRO was pragmatic in the HH programme trying to draw on organisations with the best capabilities internationally. International precedents were important in providing incentives to

[139] See Lorentzen (2005)

initiate research into HH technologies, in particular Australian, UK and US efforts in coal mining were discussed. Among these international sources the skills developed within the British Board of Coal played an important role in South Africa's ability to create innovative new HH technologies. Overall this existing body of research created an important incentive for the development of South African HH technologies by giving a foundation of knowledge that South Africa leveraged in accelerated catch-up to become at the international forefront of HH technology.

Besides this role of related foreign HH technology, the complexity of the HH system benefited from COMRO's international searching for best technical solutions across sectors. In this regard, COMRO partnered with US based Ingersoll-Rand in the initial phase of EH development because of its extensive in-house research capacity. Further examples of the international transfer and mutual development of novel technologies in this case include development of micro-emulsions by US oil companies, emergency safety valve technology from the foreign nuclear and oil industry, and specialised steel alloy development with UK and US steel producers.

5.3 Linkages and interactions

Linkages between equipment suppliers, the mines, and COMRO were particularly significant in this case. The evolution of the mining sector's system of innovation was reviewed in Section Three with particular focus on the emergence of COMRO, the sector's co-operative research organisation. A highly networked structure can therefore clearly be associated with the development of HH technology in the mining sector.

International isolation faced by the South African mining-finance houses contributed to some extent to the depth of linkages that characterised development of HH technology. In addition, internationally during the decades when HH technologies were being developed the mining sector was characterised by collaboration in production concurrent with fierce competition for securing mineral rights. Organisationally, the hierarchical structure of the South African gold industry under the mining-finance group system facilitated inter- and intra-organisational transfers of technologies and the organisation of production between mines across the Witwatersrand deposits. In COMRO is perhaps the best indicator of the cooperation that existed in research and development.

However, just as HH technologies reached commercialisation several factors transformed the previously deep connections to a point where they no longer structurally facilitated the introduction and diffusion of the HH system. First, increased internationalisation of the South African economy in the 1990s led to South African mining-finance groups to integrate and diversify operations globally, thereby undermining some of the common cause that had previously supported social capital and collaboration in the industry. Secondly, internationally mergers and acquisitions in the mining sector shifted the borders of competition and co-operation so that cooperative research and development was no longer viable among the mining firms. Thus, the scope for further collaborative development and diffusion of HH technologies was reduced, a point most clearly illustrated by the dissolution of COMRO itself.

Lastly, beginning in the 1980s as part of the general restructuring hierarchical control by the South African mining-finance groups, individual autonomy at the Witwatersrand gold mines was increased simultaneously with a reduced capacity to significantly alter operations. This led to a situation where the mines increasingly customised mining operations to suit the geology of their deposits rather than just applying standard operational practices across all of the group's mines. This further raised the barriers of path dependency for HH technologies to overcome as pneumatic based stoping became entrenched at a far more localised level than it had been previously.

The interviews in the course of this project made it clear that within the community of HH technologies linkages remain to this day with close and relatively frequent interactions between individuals and organisation. However, the loss of COMRO removed a critical champion of the technology and in the face of these additional challenges it is now dependent on the HH equipment manufacturers to promote adoption of HH technologies. As a result South Africa's HH technology continues to face severe hurdles in its diffusion in the domestic and international mining sectors. With out greater adoption of the technology in their target market most of the firms with HH capabilities appear reticent to venture into other uncertainties through the lateral migration of their technology.

5.4 Industrial policy

While State taxation and fiscal policies generally favoured the mining industry, when HH technologies were being developed these indirect measures were the only public support that these technologies received. As such this case illustrates the power and importance of intra-sectoral co-operation in fostering the productive capacity of a sector. Currently, the role played by COMRO's systemic coordination has not been appreciated in policy debates around enhancing South Africa's mining competitiveness. Despite valid criticisms of COMRO itself, with out a similar stakeholder in the sector's system of innovation it is virtually certain that no equipment supplier would ever undertake the development of a radically alternative technology like the HH system. As a result there is less likelihood that a domestically developed broad platform technology will laterally migrate in the future. Notably, so far industrial policy has also not been a significant factor in the lateral migration HH technologies. Clearly this is an area that needs further policy consideration.

This case has shown how a complex systemic technology developed for the mining sector has laterally migrated. While its economic significance to date has not been momentous, it remains a technology with significant potential in both its original sector and in others. The case has also highlighted an important era in the mining sector's system of innovation which serves is an important precedent contemporary initiatives aimed at enhancing domestic competitiveness.

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Afterword

Introduction

I would first and foremost like to thank the Human Science Research Council for providing an auspicious platform for personal growth and development by allowing me to engage in such intense research experience. The opportunity to conduct academic research under the supervision and guidance of Dr. Tomas Pogue of the IERI (whom I so honour) has been both rewarding and interesting. I am grateful for this opportunity because it has enriched my academic and Research pursuit, as I have learned both within of the classroom and on the field. I can definitely say I have grown academically, mentally and professionally.

With no prior mining experience to begin with, it started out as an immense challenge.

First draft

As I commenced to gather useful insight into the topic it allowed me to reach far beyond the surface of sensitive issues that are often not accessible or even perceptible to the average man. My direct learning about the Hydraulic technology situation, the conditions faced, the perspectives of the various stakeholders involved and the theoretical perspectives used to frame this topic has renewed my interest in the field to the extent that I am seriously considering pursuing one or more of these aspects of the project further in terms of my professional development.

In the beginning phase of the project I started out with great optimism. With no solid knowledge of the field I soon realised that I had to suppress much of my enthusiasm to ensure the topic at hand is properly tackled.

Two distinct categories of lateral migration associated with hydraulic technology were identified and my role was to scrutinise these areas in detail. First, the establishments of mining consultancies, and secondly the applications of the technology in other industries and sectors. A series of interviews were conducted with the various mining consultancies. The experience, expertise and knowledge gained from conducting these interviews were truly humbling and remarkable in the same light. Various equipment manufacturers were also identified. This however left us with a very broad overwhelming scope and serious refining was necessary.

Conference

The International Workshop on Lateral migration held at the Manhattan Hotel in Pretoria, broadened my knowledge in this regard. This gave another dimension to the project as I learned that not only within the domestic setting but also internationally this project was carried out. This being my first conference and having minimal knowledge within the mining segment sort of had to be on the absorbing end rather than more intensively involved so as to grasp the fundamental basics and I feel this workshop played a vital in the success of this project's delivery or output. During this time it was also an intriguing moment of networking with various delegates, especially the likes of Dr Adi Peterson, to explore the issue of lateral migration. During the presentation of different approaches to the issue at hand, it was great to take notice of other cases relative to lateral migration from Lea Velho, Dr Walker, Juana, Elisa and yourself Jo (since I was very keen to meet out boss).

Final draft

During and after the workshop, I was also expected to prepare for other academic presentations since during this period exams at varsity normally would run but however my efforts in this were facing impediment. Through this time I learned numerous life aspects like commitment, authenticity, discipline, decision-making and time management, which I find, building a noble character to an individual. Furthermore, my enthusiasm grew even deeper in the project since I had built psychological belonging into the project, which allowed me to allocate additional hours doing a research endeavour of this stature to exude both understanding and professionalism. At this stage confidence had submerged into my attitude and from this stage I would easily say I knew what I was doing and where I was heading.

Conclusion

As far a you would have liked to provide criticism I can only go as far as admiration for a astonishing academic endeavour that aided insightful discovery of useful information and know-how and I am hopeful that these cases case reach publication. In a nutshell I would like to emphasise my gratitude in this regard for exposing me to such majestic task and hope that our relationship has not reached its maturity. In the latter I dearly thank you.

Muti from coal: science and politics of humic substance research in South Africa

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Employment & Economic Policy Research Programme

HSRC-ESSD

February 2006

Chapter 6: Muti from Coal, Science and Politics of Humic Substance Research in South Africa

Acronyms

HIV/AIDS	Human Immunodeficiency Virus / Acquired Immune Deficiency Syndrome
CEF	Central Energy Fund
MCC	Medicines Control Council
UP	University of Pretoria
DTI	Department of Trade and Industry
NIMR	National Institute for Medical Research
NRF	National Research Foundation

1 Introduction

Humic substances are naturally occurring acids that have beneficial medicinal properties. In short, they are anti-microbial, anti-inflammatory, and anti-viral. In parts of the world they have been part of folk medicine for a long time. Some applications have been thoroughly researched, tested, and approved for sale. For example, skin infections of dogs and cats can be treated with ointments based on humic substances. This is the science dimension of this case study. It is relatively easily told.

By contrast, the politics dimension is very complicated. Due to their anti-viral effects, humic substances were used in clinical trials of HIV-positive patients. For a number of reasons, these trials were extremely controversial. The negative publicity they attracted led to the sale of the state-owned company, including its intellectual property rights, which had been at the forefront of humic substance research in South Africa, to an overseas firm.

The politics and the science of the technology behind humic substances are intensely related, albeit not in ways that in retrospect would appear to have benefited the return to public R&D in South Africa or, for that matter, human progress more generally. Due to the political imbroglio, it was never established what, if any, effects humic substances might have in the treatment of HIV/AIDS. Conversely, it was never established that they had no effects, either. Given the severity of the epidemic, this lack of knowledge comes at a high price. If humic substances might have any merit in combating HIV/AIDS, they should be further researched. If they do not, they should be added once and for all to the long list of failed attempts to find a cure for the epidemic. It appears that the politics of the case make this verification difficult. This is not optimal.

An interesting side show of this case is the management of intellectual property rights. Rights to a specific humic substance, held by a state-owned company in South Africa, were sold for a few million Rand to an overseas company that now has the rights to worldwide royalties outside Africa. In short, while the initial investment that led to the patented technology was made in South Africa, a major portion of the gains from the investment will eventually be collected abroad. The national return on investment in public R&D was therefore decidedly poor. Perhaps more significantly, control over technological assets created in a developing country ended up in a developed country.[140] In a world in which command over knowledge assets is increasingly important, this is also not optimal.

Muti from coal epitomises lateral migration. South Africa literally sits on brown coal. It is the third biggest producer in the world, mining about 35 million tons a year. Coal accounts for more than 90 per cent of the country's energy supply. The processes associated with generating this technology started with wet oxidisation of bituminous coal and later changed to using a plant source to synthesise humic substances from carbohydrates.

The paper proceeds as follows. Section 2 chronicles research of humic substances in South Africa. Section 3 surveys the literature on humic substances, focusing on pharmacological aspects. It tries to establish what we do and what we do not know about the medicinal properties of these acids, and to differentiate quackery from serious science. Section 4 discusses the intellectual property dimension. Section 5 briefly touches on absorptive capacities. Section 6 concludes with recommendations for public policy.

[140] The overseas patent holder eventually renegotiated its agreement with the South African firm that arranged the sale of the patents whereby the latter secured worldwide production and African marketing rights.

2 Research on humic substances in South Africa

The central institution behind research into humic substances in South Africa was Enerkom, the former research branch of the Central Energy Fund (CEF), the state oil agency. CEF is a private company governed by the CEF Act. Its one non-transferable share is held by the state and the company is controlled by the Minister of Energy and Minerals (www.cef.co.za).

In the 1980s, CEF mandated Enerkom to research alternative uses for coal. Enerkom's scientists focused on humic substances. They occur naturally in the soil and in stream water where they account for some 50 per cent of the dissolved organic carbon. These acids are good fertilisers; humic acid stimulates crop yield while fulvic acid is a nutrient with beneficial properties for plant growth. Compost and peat contain a lot of humic substances. Subjected to pressure and temperatures over very long periods of time, peat becomes coal.

From 1984 Enerkom developed a process which essentially reversed the process by which coal is formed – instead of humic substances losing oxygen that over millions of years creates coal, the scientists oxidised coal back to humic and fulvic acid, naming them Oxihumate and Oxifulvate, respectively. The process was successful and Enerkom registered patents in South Africa and in the most important developed economies. However, the cost of oxidisation was prohibitively high for use of the product in agriculture. Enerkom therefore wanted to explore alternative uses. According to anecdotal evidence, humic substances might have beneficial medicinal properties. For example, humic acids are widely used as folk medicine in East Asia, and peat had reportedly helped in the treatment of amputations and similar serious wounds during World War I. Yet the evidence was merely observational and had never been systematically researched.

It was for this reason that in 1998 Enerkom which was located in Pretoria approached the Department of Immunology at the University of Pretoria (UP), proposing collaborative research into the medicinal properties of humic acid. It struck an agreement with a research team led by Professor Connie Medlen, an immunologist who later transferred to UP's Department of Pharmacology.[141] Subsequently her team undertook a series of in vitro and animal tests.

2.1 Research on humic acid

The test results showed that humic acid has anti-inflammatory, antimicrobial, and antiviral effects (e.g. Jooné et al. 2001, 2003; van Rensburg et al. 2002). For example, the administration of humic acid in animal trials led to the suppression of the rejection of cell transplants by the immune system of the host. It also suppressed a contact hypersensitivity reaction. The same effects were seen on isolated phagocytes in that there was a decrease in adhesion molecules associated with the inflammation. At the same time, however, lymphocytes isolated from blood drawn from HIV positive patients that had been treated with humic acid for two weeks showed an increase in proliferation when stimulated with a non-specific stimulant. In other words, the cell-mediated immune system, greatly compromised in HIV positive patients, was stimulated while the phagocyte part associated with the inflammation was suppressed.

Because of the antiviral effects, in 1999 the team sought and gained permission for a clinical trial at Kalafong, an academic clinic in Gauteng. The Medicines Control Council (MCC) limited the trial to two weeks' duration out of concern that the HIV might develop resistance. Hence it was not possible to assess efficacy because the viral

[141] Medlen publishes under the name of Van Rensburg.

load does not sufficiently decrease in such a short period of time. What the trial did show, however, was that humic acid was non-toxic.[142] In addition, patients on Oxihumate put on weight and their general condition appeared to improve. These results were presented to an international peer audience and also published (Botes et al. 2000, 2002; Van Rensburg 2000, Van Rensburg et al. 1999, Van Rensburg et al. 2001).

Funding for this research came not just from Enerkom but also, in the form of co-financing, from THRIP, a financing vehicle in support of science-industry interaction run by the South African Department of Trade and Industry (DTI).

Upon the invitation of the Chief of the Defence Force in Tanzania, the team subsequently undertook a placebo-controlled clinical trial at the Lugalo military hospital in Dar Es-Salaam which began in late 1999. At this point the story gets complicated. The ethics committee at UP had approved the trial. Permission from the MCC was not necessary because the trial was to take place outside South Africa. Whether or not the team had permission from the South African Department of Health to import blood samples from the hospital for analysis is a matter of contention. In Tanzania, the National Institute for Medical Research (NIMR) argued with the military over who had jurisdiction in this matter. The NIMR claimed responsibility over any clinical trial in the country, while the military argued that trials concerning its personnel were exempt from this rule. Whatever the merits of these arguments, the fact that they came to the fore at all suggests that preparations for such a sensitive trial were not handled with the requisite diligence. It is furthermore clear that the mere existence of these arguments did not help the research team's cause.

The relative merits of this trial were never properly assessed, let alone peer-reviewed. The reason for this is not exactly straightforward. Four years prior to this trial, a clinical technician from UP had peddled a substance called Virodene as an HIV/AIDS cure. Virodene contained a highly toxic industrial solvent. The fact that the woman behind this campaign, Olga Visser, had been given the opportunity to present her case to the South African cabinet became a major embarrassment to a government that had already attracted widespread criticism for its handling of the HIV/AIDS crisis. In a curious twist of fate, Visser had also been testing her concoction at Lugalo hospital.

When this became more widely known, the Tanzanian authorities expelled her from the country. A political uproar involving primarily Tanzanian authorities and South African media ensued that ultimately led to the unceremonious discontinuation of the Oxihumate trial. Ethics experts raised the question as to why soldiers were used for the trial, normally a group of people one would want to avoid – just like prisoners or other institutionalised groups of people – because they are typically not at liberty to decide for themselves. The Mail&Guardian, an important South African weekly, reported on the story in September and October 2001 (Deane, Macfarlane, Soggot 2001, Soggot and Macfarlane 2001). Not surprisingly, the articles were very critical. This must be seen in the context of a political environment that had for some time at the highest levels tolerated and created space for quackery and thus understandably led to suspicion of any new "wonder drug".

In turn, the relevant South African authorities had presumably no appetite for yet another HIV/AIDS scandal. Enerkom was swiftly liquidated (CEF Washes Its Hand of Enerkom 2002). The company still formally exists as a shell but its plant and equipment were sold and the entire staff was laid off. Since ultimately the company

[142] A two-week trial is not sufficient to determine safety. But dosages in the trial reached up to 8g/day and exceeded the prescribed dosages by two to four times. In addition, animal toxicity tests found no ill effects on the pathological parameters monitored for up to 1 gram per kilo bodyweight.

had never yet produced anything of commercial value – its registration as a research entity did not allow it to undertake sales - the return on investment (to the tune of R80-120 million in total) was decidedly poor. The ultimate reason for the liquidation was an attempt by management and their political masters to get out of the bad publicity that had been generated.

The liquidation implied an end to the funding the team had received from Enerkom thanks to which it had managed to finance not just the research but also a few postgraduate students. However the academic output resulting from the four years of funding was considerable.

Subsequently a former Enerkom employee who continued to believe in the value of humic substances set up a company called Unique Formulations. He substituted Enerkom's production of humic substances with a source imported from Australia whereby humic acid was generated from brown coal. This practice also exists in Russia, India, and Germany. Since brown coal is the softest available coal, it requires no oxidisation; the humic acid can basically be extracted. With a soluble humate content of at least 96 per cent, this is a much cheaper and better product than the oxidised version at a maximum 33 per cent. Among other things, it reduces the required intake compared to Enerkom's product. Unique Formulations sells a range of vitamins and herbal medicines and markets humic acid as a food supplement. However, since there has never been much uptake, the company was not interested in investing in further research of the product.

The UP team, on the other hand, continued with its trials, using the humic acid capsulated by Unique Formulations. At the time of writing, it was engaged in a clinical trial on hay fever and was planning another one on arthritis. The availability of the product as a food supplement considerably lowers the threshold for permission of clinical trials.

In sum, although the product is currently freely available on the market (as a food supplement), it is not being traded for its potential medicinal properties (e.g. against hay fever) because they have never been properly demonstrated. Even the humic acid sold for animals has apparently never been subjected to a placebo-controlled trial. The UP team's claim to fame is then to be the first group to have undertaken preliminary scientific tests of its effects on use in humans and animals.

2.2 Research on fulvic acid

Fulvic acid also has interesting properties. Fulvic acid has anti-inflammatory and antimicrobial effects and lends itelf particularly to topical applications, such as for psioriasis and eczema. The team at UP described the anti-inflammatory properties in a mouse model of contact hypersensitivity as well as in atopic dermal reactions in humans (Snyman et al. 2002, Van Rensburg, Malfeld, and Dekker 2001, Van Rensburg, Van Straten, and Dekker 2000). The MCC approved fulvic acid as a veterinary treatment for dogs and cats suffering from pyotraumatic dermatitis or eczema. This was a direct outcome of the team's research. Although it is not yet clear how exactly fulvic acid works, preliminary results indicate that it scavenges free radicals and inhibits specific phagocytic and lymphocytic cellular functions.

Research on fulvic acid is continuing in disparate ways. The people involved always appear to have a direct or indirect connection to the now defunct Enerkom. For example, Pfeinsmith Ltd, the overseas company that bought the entire portfolio of Enerkom's intellectual property rights – some 128 patents in total – granted the exploitation of this intellectual property in Africa to the South African company that arranged the sale. This company is now called Secomet (www.secomet.com). It operates out of the Techno Park in Stellenbosch near Cape Town.

Secomet has identified a new source of fulvic acid, based on carbohydrates derived from plants. The advantage of deriving fulvic acid from what is essentially a food source is that unlike coal it does not contain traces of toxic metals such as magnesium, chrome, or aluminium. These levels may be very low in fulvic acid derived from coal but it is obviously better not to encounter them at all.

Secomet markets a variety of extracts based on fulvic acid. It had the anti-microbial efficacy of the plant extracts it uses tested in vitro by the School of Child & Adolescent Health at the University of Cape Town. The lab reported growth inhibitions of 16 bacterial organisms to each of the four plant extracts tested, and recommended further research into the active component (De Wet n.d.). In addition, in 2005 Secomet contracted ViroLogic, a lab in California, to evaluate its product against ten strains of HIV in vitro. In vitro work undertaken at the Department of Medical Virology at the University of Cape Town also confirmed antiretroviral activity.

Secomet contacted the UP team in 2005 to explore R&D cooperation on fulvic acid. Initial understanding is that they will contribute R200,000 toward the funding of a PhD student to work on the project for two years, specifically on a clinical trial focusing on eczema.

In sum, humic and fulvic acids are still being investigated for their medicinal properties. The next section discusses how serious this research is.

3 The relative scientific merit of research on humic substances

If humic substances had not demonstrated antiviral properties in vitro which led to the clinical HIV/AIDS trials, pharmacological research would have been limited to their antimicrobial and anti-inflammatory effects. It would then in all likelihood not have been politicised. This is relevant for the project to which this case contributes. Without the scandal caused by the Tanzanian episode, Enerkom would conceivably not have been sold and the intellectual property rights would have stayed in the country. South Africa would perhaps have successfully pioneered one or more new drugs and been in a position to reap the benefits from their commercialisation. In retrospect, it is thus important to understand the scientific merit of research that nolens volens effectively truncated work on what appeared a promising new technology.

Humic substances have a long therapeutic history. They have been used in mud baths to treat rheumatic conditions (Baatz 1988, Kleinschmidt 1988, Kovarik 1988, Lent 1988), for the prevention of wound infections in World War I (Haanel 1924, Van Beneden 1971), and as a tonic for liver and gastric ailments (Kallus 1964). What is known about humic substances is that they appear to chelate toxic compounds (Marx and Heumann 1999, Nifant'eva et al. 1999, Sauvant et al. 1999, Shanmukhappa and Meelaktan 1990, and Stackhouse and Benson 1989) and absorb xenobiotics (Nielsen et al. 1997, Proen and Zupancic-Kralj 2000), mutagens (Ferrara et al. 2000), and mycotoxins (Van Rensburg et al. 2002).

Commercially available medications based on humic acid are antibacterial, antitoxic, anti-ulcerogenic, anti-allergic, and anti-inflammatory (Shepetkin et al. 2002). Anti-arthritic effects are also known (Goel et al. 1990, Iubitska and Ivanov 1999, Kelginbaev et al. 1973, Kleinschmidt 1988, Soliev 1983, Suleimanov 1972), as is activity against the herpes simplex virus (Thiel et al. 1977) and several types of influenza type A and B viruses (Hils et al. 1986). However, none of these findings have been subjected to clinical trials.

Research on fulvic acid is much rarer. The UP team established antimicrobial, antiviral, and anti-inflammatory activity in a series of in vitro and in vivo trials (Van Rensburg et al. 2000, 2001, Snyman et al. 2002). The results suggested that fulvic acid, applied topically, might be a safe and effective treatment for skin infections caused by pathogenic bacteria and Herpes Simplex Virus-1 as well of inflammatory conditions of the skin. Only clinical trials can identify the effects on specific conditions such as fever blisters, urticaria, acute eczematous dermatitis, psoriasis and acne vulgaris.

Clinical trials may of course fail to confirm the expected results. But this research has been subjected to peer review and is not suspect. The same cannot be said about all lobbies associated with humic substances.

One group with an extensive website claims that "[f]ulvic acid has the potential to heal the Earth!" (www.livearth.com/articles/art5.htm). Another one hails that "[f]ulvic acid holds the keys to prevention, healing, and elimination of the world's diseases" (www.fulvic.com). This includes the contention that fulvic acid effectively and safely kills the HIV/AIDS virus. These claims are at best unproven and at worst plain silly and morally abhorrent. They are important to note, however, because they appear to influence the conditions under which serious research can be undertaken, especially with respect to furthering the investigations into the antiviral properties of humic substances – for obvious reasons a highly charged topic.

It is hence important to review what is and what is not known about humic substances and HIV/AIDS. Researchers based in Germany first showed the anti-HIV activity of humic acid in cell culture (Schneider et al. 1996). Hence when the UP team started its own investigations, there was nothing wrong with probing the issue further. Its in vitro research showed that humic acid impacts on the cell mediated immunity necessary to cope with opportunistic infections by stimulating lymphocyte proliferation (Joonè et al. 2003, Van Rensburg et al. 1999, 2000, 2001, 2002). It also inhibited the damage done by and to inflammatory cells (Jooné et al. 2001; see also Gau et al 2000). This result was also obtained in vivo in the Kalafong clinical trial (Botes et al. 2000, 2003, Jooné et al. 2003). The trial lasted only two weeks but the patients on humic acid gained weight compared to the placebo group.

The clinical trial in Tanzania lasted for roughly a year and was administered to 350 HIV-positive adults, with very high median viral loads. These patients were on no previous HIV/AIDS treatment regimen. During the first three months the trial was placebo controlled. The viral load and the CD4 counts of the treatment group stabilized during this period. Hence they did not improve. But other non-specific disease parameters of disease progression – such as weight, WHO performance status and so on – improved significantly. This result still showed after 12 months; this may be due to oxihumate but could also be due to nutrition or other factors.

Owing to pressure by the local doctors – who believed that oxihumate had beneficial effects – to make the substance available to all patients, the entire group received it for the following nine months. The absence of a control group plus problems with missing data made it impossible to analyse the results conclusively. However, both the viral load and the CD4 counts of the group as a whole deteriorated from months 4 to 12. Patients tolerated oxihumate well and direct drug-related toxicity or side effects were not evident.

In essence, the study suggested that humic acid may improve the quality of life of HIV/AIDS patients. It might be possible to combine it with ARVs so as to obtain a reduction in viral loads and an increase in CD4 counts, followed by a period of parameter stabilisation during which humic acid is administered alone. If this were successful, it would minimize the side effects of ARVs while still exploiting their efficacy and increase the general wellbeing of patients.

Whether this would justify undertaking a clinical trial depends on how one views the opportunity costs. One the one hand, with the help of a range of effective and reasonably safe ARVs HIV can be turned into a chronic condition. Control over side effects has improved as well. Arguably much benefit is to be gained from researching new ways to administer the drugs and how further to omit their undesirable features. Additional challenges include the need to allow for structured treatment breaks and to come up with successor drugs that handle problems of resistance. On the other hand, there might be a role for humic acid, for example during treatment breaks. Since without clinical trials one will never know, the question is how the private or public sectors assess the potential financial or public-good return on the investment in a clinical trial.

Secomet sponsors research on the antiretroviral properties of fulvic acid at the Medical Virology Department at the University of Cape Town. Results from laboratory tests suggest that fulvic acid controls the contagiousness of the virus and prevents it from infecting new cells. If this would work in people is an open question. On its website, Secomet reports anecdotal evidence of people whose viral load has dropped after taking its product Seco V. But if this is causal or coincidental can again of course only become evident in a clinical trial.

4 Intellectual property

Unlike humic acids, fulvic acids had never been described for medicinal use before 1999. Hence Medlen and her counterpart at Enerkom, Dekker, registered an international patent in South Africa on the product and its applications (Patent number WO 0019999; AU5992399) as co-inventors. Medlen signed off her rights to Enerkom. In the absence of a fee, this cessation suggests that UP's Technology Transfer Office had little to no experience with harvesting the fruits of intellectual property developed at the university.

Unlike the process patent concerning the oxidisation of humic acid, this patent was commercially much more viable. A producer of humic acid from whatever source has not much of an incentive to invest in research insofar the substance per se is not patentable. The results would therefore be in the public domain and anybody could walk away with them. In 2003, a foreign company by the name of Pfeinsmith acquired Enerkom's patent portfolio through a South African middleman who negotiated that the rights to the manufacture and sale of fulvic acid in all of Africa would remain with himself. Pfeinsmith then had all patents assigned from Enerkom to itself, a process that in late 2005 appears pretty much complete, allowing it to collect royalties worldwide from any distributor of the substance. This agreement was later amended to assign worldwide production and African distribution rights to the South African company and international marketing rights to Pfeinsmith.

In sum, quite apart from the merits of humic substances in treating a variety of conditions, intellectual property created in South Africa at considerable cost to the public has led to income streams accruing to an outside entity that reportedly paid a fraction of the original investment for the rights to exploit the results from research on humic acid and to commercialise fulvic acid. Although knowledge intensification did take place, the technology in question emigrated, leaving little trace in its country of origin. To date the whole exercise did not meet its objectives of furthering industrial diversification away from coal merely as a source of fuel.

Rents dissipated out of the country. But IP issues also concern the relationship between Enerkom and UP. In retrospect it would seem that UP, by signing off its rights to Enerkom, did not receive benefits commensurate to its input. Incentives to the individual scientists and to the institution as a whole would thus not appear strong enough to foster a climate conducive to innovation. Put differently, if UP had sold its contribution to the development of the technology at a higher price, it might have been able to fund further those aspects of the research not covered by patent protection. Alternatively, if it had insisted on retaining ownership control over the technology, the intellectual property might have never left the country. What seems clear is that technology transfer offices at universities must learn better to reconcile incentive and reward for their academic communities so as to spur innovative activities in a supportive environment, with lasting benefits for national technological development.

5 The role and relative importance of the team at UP

The reason Enerkom originally approached Prof. Medlen was somewhat accidental. Immunology was of course her area of research but she had never thought about humic substances per se. Had she not been interested in cooperating with Enerkom, the company could have approached pretty much any university in the country that undertakes drug development. Of course, UP was very close to Enerkom, so the communication was easy and convenient.

In general, Prof. Medlen's immunology unit is research intensive. It continuously trains postgraduate students, including on this project. Overall size was small, however; only some five staff were full-time researchers. At no point in time was there more than a handful of people working on humic substances. Hence the human capital associated with research on humic substances was highly concentrated and somewhat thin on the ground; if the UP group had for whatever reason decided to leave the country, research capacity in South Africa would have been severely affected. The pharmacology unit is somewhat bigger and more comprehensive. The head of department is a clinical pharmacologist and can therefore lead clinical trials. In essence, the department can go all the way from in vitro experiments via animal experiments to human trials.

At the moment funds for research into humic substances are available from the National Research Foundation (NRF) to the tune of some R200,000. This is not much but it is better than the dry years following the demise of Enerkom and the concomitant interruption in THRIP funds.

6 Conclusion

Why is this story worth telling? First, it demonstrates a dedicated and sophisticated attempt at downstream beneficiation, from coal as a source of fuel to coal as a source of medicine, involving government agencies, universities, and the private sector. Second, it produced results that under normal circumstances are likely to have led to further investigation. Third, science obviously does not happen in a vacuum. In this case, the research became embroiled in a political conflict over misguided HIV/AIDS research that proved to be its undoing. Fourth, it would appear that the management of the research project – independently of its scientific merits – left something to be desired, both inside and outside the university. Fifth, and most importantly, technological knowledge developed in and funded by South Africa left the country without any apparent gain in the country in return for the investment undertaken. Technologically, this is not a success story but more a litany of failures.

These points carry some lessons. The first is that knowledge intensification as a strategic activity driven by government in conjunction with the science sector can work. In fact, after muti from coal, South Africa is currently investing in muti from gold. A partnership consisting of Mintek, a science council in minerals and mining, and Harmony, a gold mining house, initiated biomedical research on the anti-cancer, anti-HIV, and anti-malaria effects of gold. A number of active compounds with anti-cancer properties have been identified and now need to undergo testing. Funding for this project comes from private and public sources both in South Africa and abroad (James 2005).

The second lesson is that political interference can be highly detrimental to scientific pursuit. This is not an argument in favour of leaving scientists to their own devices, especially when they are funded from the public purse. Yet the politics-science interface in this case was evidently not ideal. This study has discussed evidence, partly produced in South Africa, that humic substances are non-toxic, non-mutagenic, and non-teratogenic. They stimulate the cell-mediated immune system, inhibit inflammatory reactions, inactivate the growth of certain viruses, and protect against environmental toxins. In addition, they are also relatively cheap. This calls for more clinical research to assess their efficacy and selectivity as a drug for the treatment of diseases associated with viral and other opportunistic infections as well as inflammatory conditions such as autoimmune diseases and allergies. These are among the most common diseases on earth, they afflict large numbers of people in Africa and, if treated successfully, would improve livelihoods and enhance economic development more generally.

With respect to the most controversial part of the research – its possible anti-HIV/AIDS properties – it is worth remembering that absence of evidence does not equal the evidence of absence. To be sure, where human health or lives are at stake, quacks must be dealt with, and government would be well advised to pay attention to what the scientific community has to say in this regard. At the same time, however, if serious scientific inquiry suggests that a substance may be effective in treating this country's worst disease, it should be evaluated on merit only.

The third lesson is that good government intentions and highly developed local scientific capabilities are not sufficient to guarantee beneficial outcomes in favour of making the most of resource-intensive sectors. Research needs to be managed to be successful. This includes managing the relationship between client and contractor in a transparent way. It also requires a sophisticated understanding of intellectual property issues between the local stakeholders and between them and any foreign counterparts. The lack of documentation, the secrecy, and the amount of incorrect information surrounding this case are abysmal. They directly and indirectly impede learning about what works and what does not work in making life for a lot of people less miserable. As such, they stand in the way of human progress.

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From coffee production to machines for optical selection:
A case of lateral migration in Costa Rica

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February 2006

Chapter 7: From coffee production to machines for optical selection: a case of lateral migration in Costa Rica

Abstract

This chapter presents an original case of lateral migration in Costa Rica. The case illustrated is about a domestic firm, Xeltron, producer of machines for optical selection, which was started up in the 1970s as a knowledge intensive input supplier of coffee producers. Triggered by an existing domestic demand, the company developed optical selectors for coffee beans, an innovation that allowed the increase of efficiency in the labour intensive phase of beans selection. After more than thirty years of expansion in the market of optical selectors for coffee beans, the firm is now launching new machines for the selection of plastics and emerald products. These new machines are based on the same underlying principles of those applied for the selection of grains but are directed to different, more knowledge intensive, clients. This is therefore considered to be a case of lateral migration. The chapter shows that lateral migration was facilitated by the firm founders' entrepreneurship and their technical background, and by the investment in the strengthening of the firm internal technological capabilities. Moreover, the formation of knowledge linkages with foreign actors has also been an important source of knowledge and technologies. In contrast, the linkages formed at the domestic level with the National System of Innovation seem not to have had a relevant impact on the firm process of lateral migration. Costa Rican industrial policies have also been marginally important in this respect.

Acronyms

CEO	Chief Executive Officer
EPZ	Export Processing Zone
FDI	Foreign Direct Investment
HS	Harmonised System
ICE	Instituto Costarricense de Electricidad
IS	Import Substitution
MNC	Multinational Company
NSI	National System of Innovation
R&D	Research & Development
SITC Rev.1	Standard International Trade Classification, Revision 1
USPTO	US Patent Office

1 Introduction

This chapter presents an original case of lateral migration in Costa Rica. I consider here "lateral migration" a process that occurs when a country or a region, whose production is originally highly specialised in natural-resource products, develops a new knowledge intensive industry or a new production process by way of the backward or forward inter-industry linkages formed by the natural-resource based firms. Backward linkages are formed with a firm's suppliers, while forward linkages are formed with clients. Normally, suppliers and clients are at different stages of the value chain and therefore they operate in different though interconnected industries. For example, backward linkages of coffee producers could be with providers of chemical fertilizers or, as in this case presented here, with producers of machines for selecting coffee grains. When the knowledge intensive industry, or the production process thus generated, becomes vertically related with new industries which are not natural-resource based, this is what I call lateral migration. It is lateral migration because the technology that is originally developed to supply a client operating in natural-resource industries, "migrates" to other more knowledge-intensive industries. The Costa Rican case offers an ideal setting for the study of lateral migration. During centuries the country has grounded its economy on the production of bananas and coffee. Coffee plantations are everywhere in the country. It was only at the beginning of the 1990s that the country specialization pattern shifted from natural-resource based industries to high tech sectors.

The case presented here is that of a domestic firm, which was started up in the 1970s as a knowledge intensive input supplier of coffee producers. Triggered by an existing domestic demand, the company developed optical selectors for coffee beans, an innovation that allowed to increase efficiency in the labour intensive phase of beans selection. After more than thirty years of expansion in the market of optical selectors for coffee beans, which persists being the firm strongest market, the firm is now launching new machines for the selection of plastics and emerald products. These new machines are based on the same underlying principles of those applied for the selection of grains but are directed to different, more knowledge intensive, clients. This is therefore considered to be a case of lateral migration.

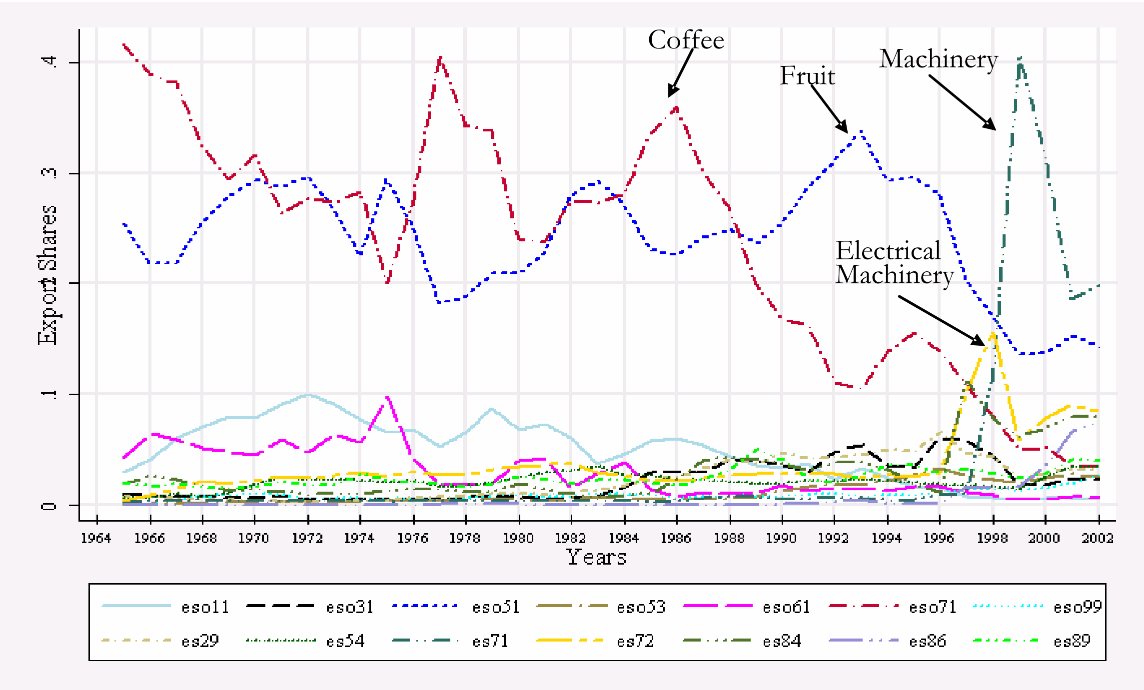
The chapter is organized as follows: Section 2 presents an overview of the Costa Rican economy in order to provide contextual information on the evolution of the country productive and export specialisation since the 1970s. Section 3 presents the firm case and provides an overview of the industry of machines for the selection of coffee beans. The remaining sections intend to understand the reasons and the factors that spurred on lateral migration. Section 4 discusses the process of firm accumulation of knowledge and the importance of absorptive capacity. Section 5 explores the role played by external and foreign linkages in the development of optical selectors. The linkages with the National System of Innovation and the country institutional and policy support are explored in Section 6 and 7. Section 8 concludes.

2 Costa Rica: from natural-resources to high tech industries[143]

The Costa Rican economy has experienced positive rates of growth since the 1950s. After a decade of high instability and strong dependence on terms of trade, in 1965 the country enforced import substitution (IS) policies, which lasted until the end of the 1970s. The first half of the 1980s was affected by the widespread Latin American financial crisis, while from 1985 onwards structural reforms and market liberalisations were promoted. In particular, the 1990s were characterised by fiscal policies to attract efficiency-seeking foreign direct investment (FDI), especially in high technology industries (Mortimore, 2002).

Historically, the industrial specialisation pattern of the country has been in natural-resources. As shown in figure 16, at the beginning of the IS period, exports were composed mainly of coffee, bananas and processed fresh fruit. As argued by Azofeifa-Villalobos (1996) and Céspedes and Jimenez (1994) the favourable world coffee price during the 1970s and the first part of the 1980s, has favoured Costa Rican economic growth. However, at the end of the 1980s, the share of these commodities, especially coffee, collapsed due to the worsening of the international prices, and, until the second half of the 1990s, no other sector grew to balance this reduction.

Figure 16 - Evolution of main export sectors' shares (2-digit SITC Rev 1)

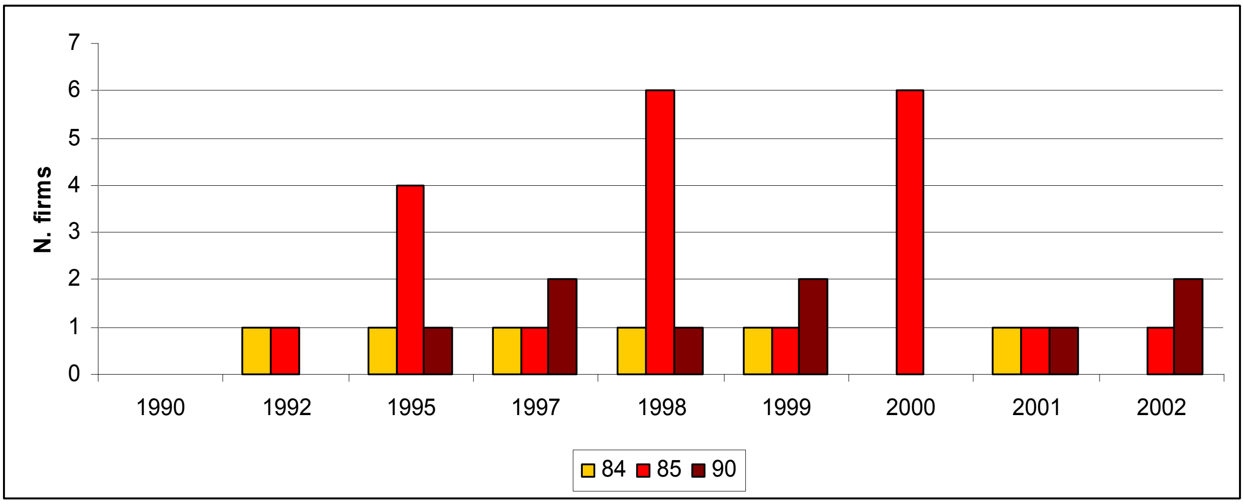


Source: Adapted from Ciarli and Giuliani (2005)

[143] This section is based on Ciarli and Giuliani (2005).

The change in the composition of exports in the second half of 1990s, especially after the investment of Intel Co. in 1997, is due to the wave of FDI investments in high tech industries, typically microprocessors (HS 84), electrical machinery (HS 85) and medical instruments (HS 90), occurred during the 1990s (see figure 17). It is worth mentioning that the change in the industrial structure towards more knowledge intensive activities has been driven and has involved only foreign investors, whereas domestic firms have only been marginally included. In fact, the domestic industry persists being dependent on resource-based industries. As reported by Ciarli and Giuliani (2005), "agricultural goods and manufactured coffee remain the two leading sectors in Costa Rican exports from the domestic economy." (p. 16) Coffee in particular, which represents more than 3 per cent of world imports, still accounts for 10 per cent of domestic exports. In this context, it is interesting to unravel the story of a small domestic firm, which has been triggered by the existence of a domestic natural-resource based industry, that of coffee production, and has managed to emerge as a highly sophisticated and knowledge intensive producer of optical selector machines.

Figure 17 - FDI in high-tech industries during the 1990s



Note: The sectors are classified using the Harmonized System 1996/2002. HS 84 indicates microprocessors, HS 85 indicates electrical machinery and HS 90 medical instruments. See http://unstats.un.org/unsd/comtrade/default.aspx.

Source: Own elaboration of Procomer (2004).

3 Introduction to the case and industry overview

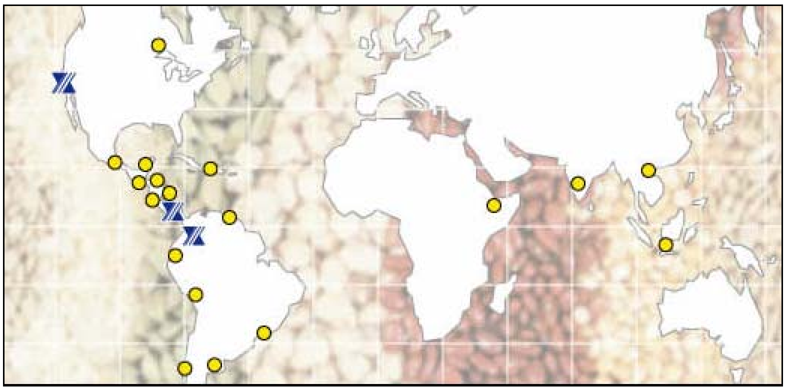
This case is based on evidence collected through a series of in-depth interviews to the CEO and the Director of R&D of Xeltron (http://www.xeltron.com), a Costa Rican producer of **machines for colour sorting** of food (e.g. coffee, rice, beans, nuts) and non-food products (i.e. plastics and emerald). The technology for colour sorting was originally developed as an input to the production of coffee, a natural resource historically driving the Costa Rican economy. This is considered a case of lateral migration at two levels: at the country level because a knowledge intensive industry was laterally created out of the production of coffee. At the company-level, as Xeltron started from modifying an imported technology used to sort coffee beans and 'migrated' to more sophisticated technologies, developing in-house new machines for sorting other types of grains, such as rice, beans etc. and even to other types of non-food materials. The firm is located in Tres Rios between the Capital city of Costa Rica, San José and Cartago, in a stand-alone export processing zone (figure 18).

Figure 18 - Xeltron: the plant

Source: www.xeltron.com

Xeltron is a domestic firm founded by two Costa Rican engineers in 1974. The company currently employs around 80 people, among which 10 are technical professionals with a university degree (2005 data). Their sales range among three and six millions dollars per year, depending on the trend of the markets for commodities. The company started exporting in 1988 and to date it exports about 98 per cent of its production. Over the years, the company has strengthened its marketing capabilities and built up a global customer-service network, which, by and large, includes countries with a strong specialisation the production of coffee (figure 19).

Figure 19 - Xeltron customer services worldwide



Source: www.xeltron.com

The production of machines for cleaning, sorting, screening and grading seeds, corresponding to the HS 2002/1996/1992 classifications codes 843710 and 847410, is mainly concentrated in advanced countries (http://unstats.un.org/unsd/comtrade/). As reported in table 16, European countries, Japan and the USA are the world top exporters. Not surprisingly, then, within this classification Costa Rica contributes only to a small percentage of the worldwide export.[144]

Table 16 - The market of machines for cleaning, sorting, screening and grading seeds (six-digit)

HS2002 Code	Description	Statistics in 2003	
843710	Name: Machines for cleaning/sorting/grading seed/grain/dried leguminous vegetable ... Description: Machines for cleaning/sorting/grading seed/grain/dried leguminous vegetables	**Exporting country**	**Trade value**
		EU-25	$124,900,989
		United Kingdom	$124,491,360
		Japan	$89,006,450
		Denmark	$60,972,339
		USA	$56,862,362
847410	Name: Sorting/screening/separating/washing machines for earth/stone/ores/oth. min ... Description: Sorting/screening/separating/washing machines for earth/stone/ores/oth. min. subs., in solid (incl. powder/paste) form	**Exporting country**	**Trade value**
		United Kingdom	$672,118,730
		EU-25	$468,175,549
		Germany	$344,082,688
		USA	$251,133,261
		Canada	$101,513,623
		Other countries (amongst which Costa Rica)	$797,070,422
		Costa Rica	$41,072

Source: Comtrade

The worldwide niche of optical sorting machine producers is rather concentrated, with only a few global leaders, such as Sortex (UK, established in 1974), Satake (USA, established in 1931), Sanmak (Brasil, established in 1980) and Selgron (Brasil, established in 1980), besides Xeltron. Among them, Xeltron is a worldwide leader in the production of machines for the *selection of high quality coffee beans*. In the production of other types of machines, Sateke and Sortex are instead the market leaders, including technologies for the selection of low quality coffee beans. If we consider the market of machines for colour sorting of coffee beans, we observe a strong penetration of Xeltron in most of the Latin American markets (table 17). As mentioned, this is particularly so for high quality coffee grains (Arábigo Robusta (Calidad)). For other types of grains (Robusta) Xeltron's market share is sensibly lower, especially in Indonesia and Vietnam.

[144] One should acknowledge that this classification is an approximation of the size of the industry, since, even at the six-digit, the classification is quite broad: Besides machine for sorting and selecting grains or other materials, it includes machines for cleaning, grading, washing and so on.

Table 17 - Xeltron market share in the market of machines for the selection of coffee beans

Machines for the selection of coffee beans	Country	Xeltron (%)	Competition (%)
Arábigo Robusta (Calidad)	México	84	16
	Guatemala	86	14
	Honduras	82	18
	Salvador	88	13
	Nicaragua	80	20
	Costa Rica	97	3
	Panamá	100	0
	Colombia	85	15
	Venezuela	84	16
	Ecuador	90	10
	Perú	95	5
	Total Calidad	***87***	***13***
Robusta	Brazil	59	41
	Indonesia	35	65
	Vietnam	32	68
	Total Robusta	***55***	***45***
Total		***76***	***24***

Source: Courtesy of Xeltron (2005)

Recently, Xeltron has started the development of machineries for the selection of other types of materials, such as plastics. This represents the essence of the lateral migration process. However, in spite of having the sufficient internal capabilities to master the technology, the presence of Xeltron in these markets is still very minor. This is considered to be due to the lack of other complementary assets (Teece, 1986), such as access to markets. The company is making an effort in this direction, which classifies it as an incipient process of lateral migration.

4 The beginning and the accumulation of firm capabilities

The historical context in which Xeltron was created, the 1970s, was one where Costa Rica specialization pattern was based mainly on coffee and banana production. It was also a period of import substitution (Section 2). These conditions can be considered the seeds that spur on the entrepreneurship of two Costa Rican engineers, who, at that time, were often contracted to repair imported coffee beans selectors. During the 1960s and 1970s, in fact, coffee producers started to import specific machineries to automate the process of quality sorting in order to reduce the costs of such a labour intensive phase. When these machines incurred into technical problems that impeded their functioning, coffee producers resorted to domestic engineers. In those times, the country had already a very well trained pool of mechanical engineers, most of them working for the *Instituto Costarricense de Electricidad* (ICE), the national provider of electric power. With time, these engineers realized that they could not only adjust imported machineries but produce them, improving upon the existing technology. Therefore in 1974, a group of engineers, formerly employed by a local chemical firm

Kativo,[145] founded the firm Xeltron. The founders had been trained as engineers in domestic universities – the Tecnologico de Cartago and the Universidad de Costa Rica. They had skills in mechanical and electronic engineering. As such, the company was the result of a domestic entrepreneurial initiative, based on self-financing of the original founders.[146]

In developing new sorting machines, they introduced considerable innovations:

> They in fact took on the challenge of going beyond the existing colorimetric sorting and began extensive research and development to ensure the separation of the various defected beans as well as the removal of those that were unacceptable, based on one principal idea: measuring the colour of the beans. In 1974, they developed an optical analyzer that with a sophisticated electronic system and mathematical fundamentals, scientifically and precisely analyze the bean's colour. The first patents were obtained and Xeltron, a company that designs, makes and markets machinery that electronically sorts grains and seeds by colour, was formed (Source: www.xeltron.com).

More in detail, Xeltron was a pioneer in developing a system of colometric sorting based on a mathematical measurement of the beans colour. As the CEO of the company puts it:

> Xeltron technology was the first system of circumferential analysis of colours to be used in the selection of grains. In this technology we decompose the colour of the grain in three rays of different wave length and we analyse them with great precision, through mathematical means, in order to be able to determine precisely what is the colour of each grain (Own translation based on original interview with Xeltron CEO, September 2005).

Colour analyzers used by the competition up until that moment required a reference background, which ideally represented the colour of the grain which should be selected in. The selection was therefore based on comparing the grain with a reference colour, without measuring the colour *per se*. As the company CEO puts it:

> In the selection system adopted by our competitors, the grains are compared with a reference background or a cardboard specimen, which represents the ideal colour of a good product. In this way, the grain colour is not measured directly being it based on a simple comparison. (Own translation based on original interview with Xeltron CEO, September 2005).

As a consequence, the competitors' existing technology was very inaccurate and required constant re-calibration of the machine. The inaccuracy was due to the fact that the reference background represented an approximation of the ideal colour and was not able to detect all of the beans defects. In addition, this technology used analogical electronics, which was neither versatile nor user-friendly. As such, it was unsuitable for a developing country, where most of the coffee plants are located worldwide, since it required highly skilled engineers to operate.

The lack of an accurate selector for coffee beans, generated a market opportunity, which spurred Xeltron founders to develop the project of an optical colour sorting machine based on a mathematical algorithm that could actively see colours rather than passively compare them with a reference background. As said, this technology therefore did not need constant re-calibration and was more easy to use. Gerstenfeld (1998) reports that the machine developed by Xeltron makes the selection using photocells and fibre optics. Thus, "if the machines "sees" a bad bean, a solenoid puts a short blast of air against the bean and pushes the bad bean into a separate bin or on

[145] See www.protecto.net/Quienes_Somos/index.shtml for details on Kativo.

[146] When their previous employer, Kativo, was sold to a multinational company, the two engineers sold their shares of the company and used them to finance the new entrepreneurship.

to a separate conveyor belt. This all happens very quickly, perhaps 300-600 times per second" (p. 2). See figure 20 for some examples of products developed by Xeltron.

Figure 20 - Machines for optical colour sorting by Xeltron (www.xeltron.com)

Rollers	Chutes	Prisma
		

The development of the new machinery was therefore based on the understanding of the functioning of existing beans selectors, used by coffee producers in the 1970s in Costa Rica. However, its development was not the result of an incremental innovation based on *reverse-engineering* but on a **true technological advance and architectural innovation** (Henderson and Clark, 1990).

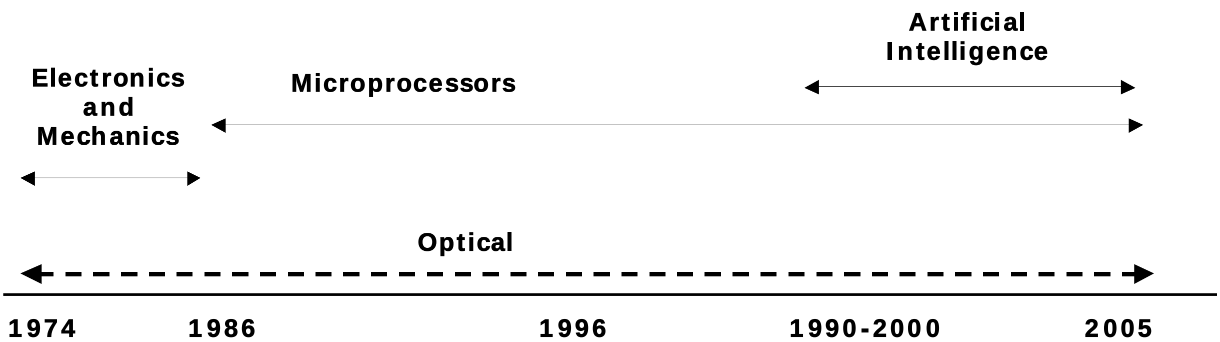
Since the very beginning Xeltron set up an R&D Laboratory, and most of the technological advances were developed internally. The R&D laboratory was established in 1975 and the first patent was granted in the 1974 by the US Patent Office (USPTO). Throughout its history, Xeltron has been granted five patents by the USPTO. Today Xeltron is a leading firm, which invests about 3-5 per cent of its sales in R&D with some peaks of 30 per cent when there is a new product development. It currently organizes the process of R&D in two stages: first, an experimental phase where they carry out basic research and second, a development phase where they carry out design and product development.

The firm employs ten technicians with skills in engineering and informatics and carries out regular training within the firm. The engineers come mainly from the neighbouring Tecnologico de Cartago and less frequently from the Universidad de Costa Rica. Training is mainly on the job, through intensive mentoring by the R&D and Production Managers. The CEO of the company says that it takes over a year before an engineer starts really contributing to the firm, as the technology is complex and very specific. This is due to the fact that engineers have to be versatile and specialized at the same time: any engineer has to learn, not only how to design and manufacture the component he or she is in charge of, e.g. motherboard and circuits design, but also how other components are designed and manufactured, thus mastering other engineering skills like optics or mechanics, software, etc. Accordingly, training involves learning about all the technologies involved in the product, and how they interact as well as the specifics of the technology in which each engineer specializes.

The process of learning within the firm was incremental and cumulative, with some technological jumps in the 1980s, 1990s and 2000s (see figure 21). As mentioned above, the firm's breakthrough was related with the introduction of optical technologies. Already in 1974, the group of founders had developed and patented an optical analyzer based on a mathematical model for absolute colour analysis that would revolutionize the local coffee industry (Gerstenfeld, 1998). Over the decades they augmented the efficiency of their machineries by incorporating new technologies, thus shifting from mechanics and analogical engineering in the 1970s to digital technologies (microprocessors) in the 1990s to artificial intelligence in 2000. The process of accumulation was based on a combination of internal R&D and the acquisition of external technologies.

This means that Xeltron generated internally, through in-house R&D, the necessary absorptive capacity (Cohen and Levinthal, 1990) to adopt and apply new technologies to their own machineries. For example, when microprocessors where introduced in the market they implemented this opportunity by introducing them in the machineries. Over the years what the firm seems to have strengthened is the development and mastering of a highly versatile and general purpose technology (Bresnahan and Trajtenberg, 1995), based on the combination of mathematical measuring of colours with other types of knowledge (optical, digital, artificial intelligences). This is at the **core** of the lateral migration process. The technology developed for the selection of coffee beans and other food grains was in fact based on underlying mathematical principles that allowed it to be used and adapted to other types of materials, such as plastics and emerald. The flexibility of the knowledge base underlying the machines is directly tied to the original method of colometric sorting, which generates opportunities for diversifying the product into other industries. Incremental changes in the calibration and mathematical measuring of colours allows the machines to be applied to different materials, and therefore has permitted the migration from natural-resources to plastics.

Figure 21 - Accumulation of technological capabilities over time



Source: Own elaboration based on interviews to Xeltron.

The accumulation of technological capabilities is also documented by a series of patents that have been granted to Xeltron by the USPTO in-between the years 1974 and 1996 (table 18).[147]

[147] Interestingly enough, the company tried once to patent in Costa Rica but the patent application was rejected. They ultimately were granted the same patent in the US.

Table 18 - History of Xeltron's patents

Year granted	Investor(s), Assegnee, Application no.	Title. Abstract
1974(*)	Not available	Not available
1977	Castaneda F. and Jimenez R.; Xeltron S.A.; 568761	**Optical sorting apparatus**. Apparatus for optically sorting small light objects such as beans and/or grains on the basis of size and color. A feeding mechanism separates the objects one from another and delivers them in a free falling condition to an optical analysis means where each object is uniformly illuminated. The analysis is based on the amount and spectrum of reflected light which is conveyed to a pair of light transducers having different response characteristics. The electrical signals developed by the transducers are simultaneously analyzed for absolute values to determine object size and relative value of the integrated signals to determine object coloring. An annular analysis head is employed with the objects being analyzed falling through the central opening. The head is comprised of a pair of annular rings with a predetermined gap between the rings located at the central opening. Plural fiber light conducting rods are uniformly spaced about the circumference of the gap so as to collect light reflected from the object. A pair of fiber bundles are formed, each made up of rods uniformly disposed about the circumference. Each bundle of the pair provides light to a different transducer. Low pressure air introduced at the gap prevents dust or the like from masking the rod ends.
1988 (1)	Castaneda F.; Xeltron S.A.; 762543	**Control panel.** A control panel having a display for displaying selected statements from a plurality of stored statements containing one or more separate elements of alterable information; four selectively operable push-button switches; and a computer for storing the stored messages and controlling the display. The switches include left and right scroll switches and up and down-increment switches. The computer controls a cursor on the display movable left and right between one or more pre-programmed positions in each displayed statement in response to operation of the scroll switches. Each of the pre-programmed positions corresponds to one of the segments of alterable information. The scroll switches cause the computer to scroll left or right for sequentially displaying the next left or right statement. Scrolling to the next stored statement is in response to the scroll switch indicating an attempt to move the cursor left or right beyond the leftmost or rightmost pre-programmed position for the displayed statement. The computer increments up and down the segment of alterable information corresponding to the pre-programmed position to which the cursor has been moved in response to operation of the increment switches.

Year granted	**Investor(s), Assegnee, Application no.**	**Title. Abstract**
1988 (2)	Castaneda F.; Xeltron S.A.; 787534	**Process and apparatus for sorting samples of material.** An optical sorter for beans and grains, including a detector providing a signal pulse for each of the sampled objects, and a signal processor for receiving and amplifying the pulse. The signal processor measures the amplitude of the amplifier pulse and compares the amplitude value to a predetermined standard value. The pulses are counted up to a predetermined count, and the number of pulses having an amplitude value above the predetermined standard value out of the total number of counted pulses, is counted. The counted number of pulses having an amplitude above the standard value is compared to a preselected number, and the gain of the signal processor is adjusted with a negative feedback signal to adjust toward the preselected number, the counted number of pulses in the next count having an amplitude value at the predetermined standard value. The sorter uses the peak amplitude value of the pulse which is determined by taking a derivative of the signal and determining the zero crossing time of the derivative signal.
1996	Castaneda F. and Aguero A.C.; Xeltron S.A.; 129848	**Process and apparatus for sorting material.** An apparatus for optically sorting small objects such as beans has an annular analysis head with an opening through which the objects fall. Three sets of optical fibers are positioned around the analysis head opening. A first set receives radiant light reflected from the falling objects. This reflected light is digitized and input to a comparator where the reflected light is compared to a reference value and a determination as to the quality of the object is made based on color. The second set of fibers is connected to an infrared light source and transmits a curtain of light across the opening, intercepting the travel of the objects. The third set of fibers receives the infrared light and is connected to a light detector which detects when objects pass through the curtain of light. The curtain of light is preferably wider than the objects. The light detector outputs a signal having peaks caused by the widest portions of objects passing through the light curtain. The peaks correspond closely with the centers of gravity of the objects. A comparator outputs an ejection signal in response to a signal from the quality detector below the reference value and the peak produced by that object. The peaks are used to time an ejection mechanism.

Source: USPTO (http://www.uspto.gov/)

Note (*): The first patent is not recorded in the USPTO database that is available only from year 1975. The patent granted in 1974 refers to the first optical sorting machine, developed by Xeltron's engineers, as described in the beginning of Section 3.

Although patents are considered by the economic literature as a way to protect a firm's innovation and to retain a certain competitive advantage on the usage of the patented technology, the respondents at Xeltron considers that their patents in general are not very important to maintain market leadership: "*patents are worthless, product innovation is the best protection in the market*" (Own translation based on original interview with Xeltron CEO, September 2005). For example they were granted a patent in Brazil, and they had no benefits after having sustained high legal costs.[148]

5 The role of foreign technology in indigenous technological development

5.1 The importance of loosely-coupled linkages with foreign partners

Xeltron has never been foreign-owned, nor has it established equity agreements with other foreign firms. However, foreign technologies have definitely played a central role in the development of new machines by Xeltron. As shown in Section 3, over time, the firm has upgraded its knowledge base, shifting from mechanics and electronics to artificial intelligence. Apart from internal R&D, the technical knowledge is sourced externally. The upgrading process has been made possible by the advances of digital and microprocessor technologies at the international level. Foreign knowledge has been acquired through consultancies, as well as through the outsourcing of the production of key technological components mounted in Xeltron's machines.

A couple of examples of how external knowledge is integrated in the firm internal processes are reported below:

- One important breakthrough in the history of Xeltron was the development of machines that applied microprocessors, during the 1980s. This technological change was first based on a consultancy by a US engineer. During a whole year the consultant engineer developed a dedicated motherboard that could be mounted on Xeltron's machines. Since then, all the incremental changes on the motherboard were carried out internally by Xeltron.
- A second breakthrough was the development of a new polychromatic platform applied in Xeltron latest product, Genius (see table 19), which implied an architectural innovation and incorporated electronics, informatics and optical technologies. They carried out the development process with an independent US engineer (after several attempts with other consultants, which all failed), who collaborated with the internal team and finally led to the development of the new machine. Genius required 9 months to be developed and it also required several visits of Xeltron engineers to the US and to US providers of components (as, for example, Motorola).

[148] The higher costs were due to litigation. Apparently, the benefits related to the payment of the damage received by the competitor were lower than the legal costs of the litigation.

Table 19 - Genius: Xeltron latest technology - technical details

Variable Multiple Vision System (Vmvs): Latest generation technology on the modular camera and lens system (multiple), an exclusive Xeltron innovation, independently controlled or in group (variable), enable each camera to sort simultaneously and automatically a particular color defect. Module independency provides reliability and machine updating is easier.
Polychromatic Variable Illumination Systems: The innovative illumination system allows changing the color and intensity of the light, maximizing sorting precision and operating in a color spectrum that ranges from ultraviolet to infrared. Xeltron developed the best technology variable referential, to maximize color discrimination.
Colorimetric: The assignment of different cameras to basic colors and the combination of multiple tonalities is an innovation that makes the GENIUS, the only machine in the market that is truly polychromatic.
Highest Resolution: Xeltron developed sophisticated optical system, achieves a precision up to 0.3mm, which could be adjusted according to user needs; allowing clean rejections of the sorting products. As a result, minimum acceptable product is rejected.
Highest Production Capacity: (6 tray model). There are 3 variations of Genius machine, depending of the type of grain to be selected: Large Grains (almonds, nuts, pistachios, hazelnuts; among others); Average Grains (coffee, corn, beans, peanuts; among others); Small Grains (rice, sesame, pepper, sunflower seeds; among others).

Source: *www.xeltron.com*

In other cases, Xeltron outsourced the production of technological components which were designed internally. For example, most of the electronics components have been historically outsourced. Until 2003 Xeltron's engineers designed mechanical parts in-house and outsourced the production in the US, with the exception of valves which were produced by domestic suppliers. Since 2003 they have been outsourcing the assembly of robotized cards, which they also design internally. Genius, for example, has a higher content of foreign-produced components, since it employs more electronic parts. In general, the company has increased the number of components that are outsourced for production and focus more on its core activity, which is the development of optical competencies.

The components outsourced to be manufactured by the suppliers are very specialised pieces of work. They are not easily available on the market since they tend to be customized to Xeltron's needs. Thus, the cooperation agreements with other firms are based on the outsourcing of key components of the machineries that are designed and partially manufactured by Xeltron. Normally, this entails long-term agreements, in order to control that the specific components are manufactured according to the necessities of Xeltron. For this reason, Xeltron has a tendency to maintain the same suppliers over time, unless they prove not to be able to comply with the required quality standards. In other cases they even allow suppliers to try different solutions and share relevant knowledge with them. This behaviour is consistent with Sanchez and Mahoney (1996) idea of modular corporation. Thanks to the existence of standard interfaces among the product's components, the firm is able to form loosely coupled linkages with other partners worldwide, and, without the need to establish equity agreements, the partners cooperate on the manufacturing and development of the product's components.

Therefore, the company does import foreign technologies. It incorporates external technologies into colour sorting machines to improve their efficiency and accuracy. In order to do so, they either carry out joint-product development with external foreign consultants or they outsource production to foreign suppliers but control the design of the components.[149] This is likely to be due to the high specificity of the product, whose technical features are not standardized.

Finally, another way of obtaining technical knowledge is through the internet, since the company has already reached a minimum level of absorptive capacity to decode what is available on the net. Clients represent a stimulus to upgrade since they propose changes, but are not themselves sources of knowledge. No other relevant international actors or sources of knowledge are observed.

5.2 The limited role of knowledge spillovers from high tech foreign direct investors

As discussed in Section 2, in the past twenty years Costa Rica has adopted an industrialization strategy based on the attraction of high tech foreign investors, operating in the electronics, microprocessors and medical device industries. It is therefore interesting to understand to what extent Xeltron may have benefited from FDI inflows. In this respect, it should be noted that the recent wave of FDI into the country is of an efficiency-seeking nature, with very limited R&D undertaken by MNC subsidiaries at the local level (Ciarli and Giuliani, 2005). Xeltron CEO thus suggests that very limited knowledge spillovers are being generated by these subsidiaries, and that, with few exceptions, Xeltron has not established collaborative linkages with them. Collaborative linkages and transfer of knowledge have occurred in one case, with the subsidiary of AETEC (www.aetec.com/) in Costa Rica, a supplier of electronics components for Xeltron. On the whole, however, the company seem to have not benefited from the presence of foreign investors.

Having benefited little from knowledge spillovers by foreign investors operating in similar industries (e.g. microprocessors and electronic machineries) is not entirely surprising. Two interpretations are offered here. First, the company has a long history of product development. As explained in Section 3, Xeltron has undertaken a path of product development and innovation since the beginning of its operations in the 1970s. An R&D laboratory was constituted immediately afterwards, and during the 1970s and 1980s the firm has searched abroad for engineering solutions and technical knowledge. This was driven by the fact that, in that historical period, the domestic industrial structure was based on agricultural products. It was therefore difficult to find solutions and knowledge at the domestic level. This has certainly affected the behaviour of the firm in a path dependent fashion. Xeltron tailored an appropriate organisational setting through the formation of loosely coupled linkages with a selected number of foreign partners (e.g. MOTOROLA and FESTO) and used this as a strategy to innovate and compete. The formation of this type of linkages is based on the creation of trustful relationships and it takes time to consolidate (Granovetter, 1985). Therefore, when the wave of inward foreign direct investments arrived, in the second half of the 1990s, the company had already a consolidated portfolio of foreign partners. This implies that the presence of new investors in the country did not generate an immediate adjustment of the firm to the new basin of local resources. This may eventually happen, but did not happen so far.

A second interpretation of why this has not taken place is because the sharing of knowledge that underpins the generation of knowledge spillovers, is based on the complementarity of firms' knowledge bases. As suggested by Lane and Lubatkin (1998) in their study on pharmaceutical-biotechnology R&D alliances, the capacity of one firm to internalise valuable knowledge from another firm depends on the

[149] *It should be noted that Xeltron acquires only about 10 per cent of its inputs in the domestic market. Besides, according to Giuliani (2005) the inputs procured locally are of low technological content, so that the vast majority of component manufacturing is outsourced to foreign firms.*

similarity among them in terms of knowledge bases, organisational structures and compensation policies. In such a perspective, then, inter-firm *cognitive distance* inhibits firms to interact and it also functions as a limitation for the firm to share its proprietary knowledge.

These results are consistent with several studies which show that firms tend to establish alliances with firms that have overlapping technological capabilities (Arora and Gambardella 1990; Mowery et al., 1996; Mowery et al. 1998). And in fact, as suggested by Hamel (1991): "*if the skills gap between partners is too great, learning becomes almost impossible.*" (p. 97). Accordingly, a second reason for so limited interaction is the fact that high tech subsidiaries operate in different technological niches and, also, given the fact that they are primarily manufacturing plants with no R&D laboratories (Ciarli and Giuliani, 2005), the knowledge that they master is different from the one that Xeltron may potentially need (Xeltron CEO, 2005).

6 Linkages and interactions at the local level

The linkages with the National System of Innovation (NSI) or with the actors that may be part of a NSI (firms, institutions, universities etc.) are rather weak at the domestic level. Xeltron has a several suppliers and clients in Costa Rica but none of them represents a valuable source of knowledge or technology. In spite of geographic proximity, the company has established very limited knowledge linkages with domestic actors in the value chain and, as described in the previous section, it tends to source globally. Operating in the global economy and in a macroeconomic framework that supports the liberalisation of markets, the company selects worldwide the partners that are more likely to be efficient and effective. Moreover, Costa Rica is affected by a severe structural heterogeneity in the domestic industry (Ciarli and Giuliani, 2005), which implies that a wide technological gap exists between foreign and domestic firms, so that domestic firms are, by and large, more inefficient if compared with international standards.[150]

Xeltron appears to be an exception to this. Attempts to establish linkages with domestic firms have tended to fail. As an example, Xeltron tried to outsource the production of simple mechanical components at the local level, but domestic suppliers had problems of quality and precision. According to our respondent, domestic suppliers do not possess the necessary productive capabilities (Bell and Pavitt, 1993), and those which have them, are very expensive and are therefore not competitive, if compared to foreign alternatives. Therefore, Xeltron did not meet suitable domestic partners – an aspect that pushed the company to procure internationally. As the CEO mentions: "*when we need help, we do not doubt it, we go abroad*" (Own translation based on original interview with Xeltron CEO, September 2005).

As concerns the linkages with institutional bodies, Xeltron has benefited from the training of engineers, mostly by the *Instituto Tecnologico de Cartago* and also by the *Instituto Nacional de Aprendizaje,* the national training institute (http://www.ina.ac.cr/). It is worth noting that Costa Rica devolves a ratio of resources to tertiary education that is quite similar to the most developed countries (UNDP, 2003). This is consistent with the huge investment that country has undertaken since the 1960s to improve higher education and university research, setting up three universities during the

[150] The concept of structural heterogeneity has been developed by the Latin America structuralist school (Pinto, 1970; Prebisch, 1973). An industrial structure is conceived as heterogeneous when it is characterized by the co-existence of sectors or activities with normal or high labour productivity and sectors or activities with remarkably low productivity.

1970s.[151] The public universities generated the supply of scientists and engineers needed for the industrial sectors that grew in the 1960s and 1970s under the import substitution model, and also for the state owned companies and institutions in telecommunications, electricity, agriculture, industry, water supply, and infrastructure." (Rodríguez-Clare 2001, p. 4)

Even within this frame, the company CEO at Xeltron believes that the Costa Rican universities do not provide sufficiently trained engineers in the areas in which the firm specializes. This is an often-heard complaint from the private sector making the point that the programs offered by these institutions do not correspond to the needs of the productive sector (Rodriguez-Clare, 2005). In this case, the complaint concerns, first, the lack of mechanical engineers who are not only skilled in plant maintenance but also in design, and in the conceptual and creative phase of development of mechanical machinery and mechanical parts of complex electromechanical machinery. Second, the lack of engineers that posses skills specific to the firm, like optics and optotronics. As an example, the CEO at Xeltron argues that:

> [Engineers trained in Costa Rican universities] have some basis in mechanics, a little bit more in the Universidad Costa Rica and a bit more in electronics in the Tecnologico de Cartago. However, they [the domestic universities] do not manage to train the profile that we need to employ in here [Xeltron]. For example, in optics we have to train our engineers in-house, because there are no engineers trained by the university with skills in optics. In electronics isn't so bad, in mechanics is not yet fully satisfying, you do not find creative designers. What you have in the market are mechanical engineers oriented to maintenance of plants and machines, not to development or design…they are not creative…- How did you solve this lack of skills? – We have employed Costa Rican that have been educated abroad, e.g. in Israel, or that have been working abroad. The last one that we employed had worked in Suisse for 20 years. (Own translation based on original interview with Xeltron CEO, September 2005).

Shifting from training to research does not improve the picture. Barely any linkage has been established by Xeltron with domestic public institutions or universities for research purposes. The respondents argue that Costa Rican universities are not sufficiently "applied", meaning that they focus more on theoretical issues than on practical ones, making it difficult for Xeltron to interact. In the past, the company has made some attempts to connect with local universities but they never worked out. This is in line with most of the literature on university-industry linkages in Latin America, showing a very low interaction of companies with public research organizations (Arocena and Sutz, 2001). Rodriguez-Clare (2005) offers another perspective to this low interaction: "I asked Arturo Agüero [the firm R&D Directior, n.d.r.] of Xeltron why his firm did not contract out this R&D project to a university. His response was that their knowledge of this particular technology was much superior to what could be found at Costa Rican universities. This points to a more fundamental problem, namely that firms accumulate a great deal of specific knowledge that is essential for conducting new R&D. Were they to contract out an R&D project to a university, they would first have to transfer this knowledge to the university, and this would be a costly process that could easily wipe out the potential savings discussed above.

Arturo Agüero mentioned an additional reason why Xeltron was and remains reluctant to contract out its R&D with a university: university R&D carries a high potential for knowledge leaks. Thus, even if it is efficient to have universities perform a sizable share of privately-financed applied research, this would not happen because companies want to minimize leaks. This is obviously inefficient from a social point of

[151] *Now Costa Rica has four public and 50 private Universities (Buitelaar, Pérez, and Urrutia-Alvarez 2000, Rodríguez-Clare 2001, MIDEPLAN 2004)*

view, and it explains why governments would want to transfer resources to universities to perform research." (p. 81) Basically, Xeltron's limited interaction with universities has to do with the appropriability of knowledge (Arrow, 1962). As universities' historical function is that of producing public knowledge, a risk exists that the interaction with a university on research projects would limit the capacity of the firm to capture acceptable benefits associated with the exploitation of the research results (Dosi and Orsenigo, 1988).

7 Industrial policy

As stated at the beginning of this chapter, Costa Rica has implemented import substitution policies from 1965 to 1979 and, after the 1980-1984 crisis, it has opened to structural reforms and macro stabilization policies. It should be therefore noted that Xeltron was started up during the IS period and may have benefited from *infant industry* protection policies. More recently, the implementation of industrial policies directed to firms is rather scattered and limited to two main initiatives: on the one hand, the implementation of free trade zones for the attraction of foreign direct investment (http://www.procomer.com/regimen/)[152] and, on the other, the support of small and medium enterprises (Parrilli, 2003). Xeltron has benefited from 8 years of total or partial tax exemption, since it opted for an Export Processing Zone (EPZ) regime. More specifically, they have benefited from total tax exemption for 4 years, from half tax exemption for other 4 years and, until 2002, they had 30 per cent exemption. However, being part of an EPZ entails high bureaucratic loads, and strict regulations. For this reason Xeltron CEO believes that they have not benefited strongly from this type of policy for their technological advances.

> We benefited from the export processing zone regime, but bureaucracy is very complex and expensive, and controls are very strict. For example, if a piece or component is imported under a export processing zone regime, and you do not use it, you cannot dispose of it, you have to keep it or use it in some way, or carry out all the bureaucracy to dispose of it (…). It is so complicated that many entrepreneurs have exited the export processing zone regime in order to avoid all this bureaucracy. The export processing zone helps, but it could be much more efficient. Also you have to consider that we are penalized by the low service offered by the Costa Rican government, if compared to other countries where there are other EPZ (Germany, Japan, US). We pay high fees and we receive a low quality of services and infrastructures (electricity, internet, telephone..) since they are public monopolies (…). We had to pay ourselves in order to have broadband cables to get up to here. (…) The benefits of export processing zones are not enough to compensate the competitive disadvantage we have with developed countries…" Own translation based on original interview with Xeltron CEO, September 2005).

Accordingly, the CEO feels that the company would have benefited from higher government support in marketing and trade and policies to reduce taxes on R&D expenses would, for example, be most welcome.

[152] *The industrialization strategy of Costa Rica has been implemented via the establishment of free trade zones, through the Export Processing Zone Law issued in 1981. The law includes special agreements such as i) export contracts, ii) Export Processing Zones (EPZ), and iii) regimenes de perfecionamento activo, which involve different measures including tax exemptions (for both import and exports), and the provision of infrastructures and services. On the characteristics of Costa Rican EPZ see also Singa Boyenge (2003).*

8 Conclusions

What lessons can be learned about lateral migration from this study? Certainly, this is a story of a rather successful entrepreneurial initiative, given the fact that, after the liberalisation of the economy (1985), Xeltron has not been displaced by foreign competitors, as it has often occurred to domestic industries in other Central and Latin American countries (Katz, 2001). On the contrary, it has strengthened its internationalisation over time.

The first lesson that can be drawn from this study about lateral migration is related to the company starting up phase, and the second one, to its expansion and strengthening over time. The starting up of Xeltron has been spurred by an existing market opportunity generated by a domestic natural-resource intensive industry, that of coffee production. Given these conditions, a combination of fortuitous events has triggered the start up and development of the firm. An important factor in this process has undoubtedly been the professional experience of the founders and their capability to grasp the opportunity, generating an entirely innovative product. This study thus suggests that the presence of qualified engineers, trained by Costa Rican public universities, have eased the success of this entrepreneurial initiative and, eventually, it seems that they have constructed the basis for lateral migration. Furthermore, the company investment in R&D has allowed it to become progressively more competitive in the international markets. The restless effort undertaken by its engineers to pursue product innovation - also documented by the patents granted by the USPTO during the past two decades - has played a big role in this respect.

It must be acknowledged that this is a very special case of lateral migration. An aspect that makes it special is that it is basically an initiative of "lonely entrepreneurs" (Lorentzen, 2005), who have conveyed a firm to build and accumulate relevant resources for lateral migration. Lateral migration is in fact likely to be a long term process, full of impediments and accidents, and this story suggests that what matters in the first place is the firm long term effort to build internal technological capabilities, an effort which is necessarily triggered by a market opportunity. The national system of innovation and the business environment in Costa Rica seem to have only marginally affected the development of the firm, which has tended to recur to foreign sources of knowledge to sustain product innovation. This is probably due to the fact that during the 1970s and 1980s the country's domestic knowledge resources were not sufficient to endorse Xeltron innovative and pioneering effort. Domestic institutions, such as universities, have played a role in the training of human resources, but have not directly contributed to R&D or to enhance the firm innovative capability. Likewise, limited impact is attributed to the industrial policy implemented by the country. Therefore, a good combination of *chance*, firm *internal effort* and *market opportunities* seems to be what has triggered a trajectory towards lateral migration.

It is hard to foresee an alternative scenario in which industrial policies played a more central role. This story suggests that the government did not interfere much with the firm operations, not at least to facilitate them, and yet, the firm has managed to become competitive. The challenge now is to complete the process of lateral migration and to gain market shares in knowledge intensive sectors, such as plastics. A conversation with Xeltron CEO suggests that they have the necessary internal technological capabilities but lack complementary assets that would facilitate access to this new market. Should the government intervene and support this process? It is hard to say.

On the one hand, this is a case of a single entrepreneurship and not that of an entire industry, therefore a policy tailored to this specific case would not be justifiable. On the other hand, policies to facilitate the access to international markets of domestic firms could favour Xeltron's process of lateral migration. This type of policy, however, would apply to this specific case, and it may not be relevant to others. Finally, it is interesting to note that the government may have already generated the domestic conditions for lateral migration. The policies to attract high tech FDI have generated an internal demand for plastics by foreign investors (Ciarli and Giuliani, 2005). This suggests that if domestic plastic manufacturers expand their production by virtue of this new demand, this would in turn generate an internal demand opportunity for Xeltron. Accordingly, the change in the Costa Rican industrial structure, which has shifted from natural-resources to more knowledge intensive products, may be what will eventually fuel the completion of the lateral migration process at Xeltron.

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