PUBLIC ENTERPRISE, SLAVE LABOR, AND TECHNOLOGICAL LEARNING IN THE NINETEENTH-CENTURY BRAZILIAN IRON INDUSTRY[1]

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ABSTRACT

Early in the nineteenth century the Brazilian government supported the formation of three large iron works. Foreign technicians were recruited in order to implement techniques more advanced than those used among small local forges. While early on these public enterprises had some positive spillover effects, the development of indigenous technological capabilities made limited further progress during the century. While government support for the training of local personnel materialized only later, technological learning in the industry was negatively affected by the iron makers' extensive reliance on slave labor trained on the job.

Introduction

While Brazil hosts a very large share of the world reserves of iron ore, and it is nowadays a leading producer of iron and steel, its domestic iron industry was of negligible scale at the dawn of the nineteenth century. Elsewhere, around that time, a breathtaking sequence of innovations had been the backdrop for the dramatic expansion of the industry. While Britain was in the lead with respect to technological innovations,[2] their adoption by iron making enterprises in other regions held the promise to foster the growth of the industry wherever the basic natural resources needed in production were available. The influence of such inward technology transfer on the development of the Brazilian iron industry during the nineteenth century is the main focus of this paper.

Particular emphasis is given to three production centers established with direct or indirect support by the government during the second and third decade of the century. These enterprises adopted techniques of iron production that while common in more advanced industrial economies, had found no diffusion in Brazil until the 1810s. While the historical record provides evidence of technological spillovers from the activities of these enterprises early in the century, their effects appear to have been short-lived and insufficient to trigger a self-sustaining process of industry-wide technological learning. As a result, the state of the Brazilian iron industry at the end of the nineteenth century is often characterized as being substantially similar to that a century earlier. To illustrate, it can be noted that after the adoption of blast furnaces at two establishments in the 1810s, no others were erected in Brazil until the end of the century. A central goal of this paper is to explore the reasons for the limited extent of technological learning in the industry, and the resulting failure to adopt iron making techniques that were commonplace in industrializing economies.

The Portuguese crown's commitment to the development of the colony's iron ore resources led to the realization of three large scale iron works under the direction of Brazilian and foreign scientists and technologists. Their histories will be presented in turns, followed by an assessment of the evolution of the industry through the rest of the century. The spillover effects from the realization of the three big projects on the subsequent industry development are documented in the seventh section of the paper. The focus will be on the institutional features of the industry that slowed down the accumulation of technological capabilities.

Portuguese Public Policy Toward Brazilian Iron

The earliest production of iron in Brazil dates back to the year 1597 when Affonso Sardinha Filho set up two forges in the vicinity of the present town of Sorocaba (Sao Paulo). After Sardinha's death in 1629, iron making became an activity conducted on a small scale typically by the users themselves, smelting iron ore in small hearths according to a technique called *en cadinho* brought along by African slaves.[3] While a domestic market for iron implements grew around the enterprises involved in the mining of gold and diamonds particularly in the present state of Minas Gerais, domestic iron making was stifled by the mercantilist policies of the Portuguese government. Indeed, no matter how small the scale of iron production was at the time, the Portuguese court (King Pedro III and Queen Maria Francisca I) issued in 1785 an administrative order prohibiting the building of furnaces in the colony. The ban was lifted ten years later during the regency of Joao VI, whose ascent to the throne signaled a definite change in economic policies toward the colonies.

In particular, the government took an active interest in developing a local iron making industry when the Portuguese crown was forced to relocate to Brazil in 1808 as a result of the Napoleonic wars. This interest owed a great deal to the Portuguese crown's growing reliance on a cadre of civil servants who received their education in the most advanced European centers of scientific and technical research of the late eighteenth century.[4] Among these civil servants, we can identify a few men who played an important role in the later development of the iron industry.[5]

Jose' Bonifacio de Andrada e Silva (1763-1838) sailed to Portugal upon completion of his secondary education in Rio, where he took the courses in Philosophy and Law at the Universidade de Coimbra between 1783 and 1787. In 1789 Andrade e Silva was made a member of the Academia Real des Ciencias in Lisboa, and a year later he was sent on a study mission across Europe together with the fellow countryman Manoel Ferreira de Câmara. During the following ten years, these two men visited leading research societies and universities, including the Bergakademie in Freiburg, but also foundries and forges of the continent.

Câmara returned to Brazil in 1800 where he was appointed Intendente General of the Distrito Diamantino (a region partly overlapping with the province of Minas Gerais) and charged with responsibility to oversee the exploitation of mineral resources in the region.[6] Andrada e Silva remained instead in Portugal, where he was appointed professor of metallurgy at the Universidade de Coimbra, and later General Intendant of Mines and Metals of the Kingdom. In this position, he recruited three German mining engineers to serve in the Royal Corps of Military Engineers in 1803: Wilhelm Ludwig von Eschwege, Friedrich Wilhelm von Varnhagen, and Wilhelm Christian von Feldner. These three men followed the court to Brazil in 1808 and became crucial figures in the development of the Brazilian mining industries.

Already in 1800 the colonial authorities in Brazil sent a team of experts to study the feasibility of an iron smelter at Ipanema, a site close to the town of Sorocaba in the province of São Paulo. The project was approved in 1801, although construction did not begin until later. In 1808, Câmara received government approval and funding for building an iron foundry in the province of Minas Gerais. The government also provided administrative and financial support to Eschwege's plans for the construction of an iron works at Congonhas do Campo (Minas Gerais) in 1811.

These three factories represent the earliest instances of large scale production of iron in Brazil based on the adaptation of technologies that were quite common in more advanced economies. Two of them pursued the implementation of the indirect method of iron production based on blast furnaces. The third, whose initial capital was raised among private investors, adopted a less costly technique of production that in its essential elements represented a refinement of the *en cadinho* technique commonly used by local iron makers.

Fabrica Real de Ferro do Ipanema

As noted above, the colonial authorities had approved the project for an iron smelter at Ipanema as early as 1801, but no construction took place for the following nine years.[7] When actions were taken to implement the project, conflict arose about the technical characteristics of the foundry. In fact, in 1809 a first agreement entered into by the Brazilian government conferred the direction of the project to a Swedish engineer, Carl Gustav Hedberg. In addition to Hedberg, the contract provided for the relocation to Brazil of a team of between fourteen and eighteen technicians, and the transportation to Sorocaba of the equipment needed for the foundry. Shortly thereafter, in 1810, Varnhagen was also invited to draw plans for the Ipanema iron smelter. While Varnhagen proposed the construction of two blast furnaces feeding pig iron to an attached forge, Hedberg's plan adopted the direct method of iron production, including four Swedish furnaces[8] for a yearly output of 40,000 arrobas of bar iron.[9]

In spite of Varnhagen's and Eschwege's advise to the contrary, a royal commission approved Hedberg's plan and put him in control of the construction work, providing him with a capital of 48,000 cruzados and a work force of one hundred slaves. The completion of the foundry was delayed until 1814 as cost overruns kept accumulating, bringing the overall construction outlays to 200,000 cruzados.[10] The mounting evidence regarding the lack of competence of the Swedish director and its team, as well as the deceitful bargain that brought them to Ipanema, finally induced the government to dismiss Hedberg's team, but for a few technicians who were to continue operating the four furnaces. A royal order issued in December 1814 entrusted Varnhagen with the direction of the enterprise, instructing him to proceed with the building of a new foundry with two blast furnaces. Before the completion of the new foundry in 1818, Varnhagen also acquired responsibility for the operation of the existing forges because of the poor results achieved under the management of the remaining Swedish technicians.

An interesting view on the operations of the factory at Ipanema can be gleaned from the account of two German scientists, Johann Baptist von Spix and Carl Friedrich von Martius, who visited the foundry on January 9th 1818.[11] At that time, three Swedish founders were operating the four Swedish furnaces. Production with the blast furnace was on hold until the arrival of a German founder.

During their visit, Spix and Martius learned about concerns with the quality and resistance of the blast furnace material, which later turned out to be unfounded.[12] The two visitors perceived potential constraints on the expansion of output at Ipanema in the future because of the dearth of good charcoal wood. Local landowners had been required to contribute to the iron works an amount of charcoal wood proportional to their land holdings, but the two visitors thought that the supplies of wood would have soon run short in the absence of regular reforestation efforts.[13]

While the historical record is not altogether clear on the matter, shortages of fuel do not appear to have played a major role in the future operations of the foundry at Ipanema. Furthermore, Varnhagen's account indicates that during 1819 the furnace worked with a fuel mix that contained only a small fraction of charcoal. For every part of charcoal the fuel charge contained six parts of wood, predominantly from the *peroba*, a tree described as widely available in all of Brazil. Varnhagen convinced himself through experiments that smelting with wood gave better results and economized on the cost of charcoal production. In later years, he increased further the proportion of wood in the fuel mix.[14]

While the foundry achieved a reasonable level of fuel efficiency and iron recovery rates during the first years of operation, it faltered after Varnhagen's departure. In 1834, a royal commission was appointed to study the reasons for the difficulties encountered. After operating fitfully for decades the foundry was shut down in 1860, only to be reopened five years later under the stimulus of the war of Paraguay. But by the end of the century, the foundry stopped operating.[15]

Fabrica de Ferro do Morro do Pilar

Although construction began first at the Fabrica Real de Ferro do Ipanema, the first pouring of iron from a blast furnaces in Brazil took place at another site in the state of Minas Gerais. Manoel Ferreira da Câmara, by then a highly respected Brazilian mineralogist, decided in 1809 to set up a large iron works for the royal court, receiving funding and other forms of support from the latter. From Eschwege's account, locating an abundant supply of charcoal wood was the main difficulty in selecting a foundry location in Minas Gerais, as iron ore and water power were widely accessible instead. Câmara chose a location close to the Morro do Pilar, a mountain rich in iron ore, and the Rio Picão, a river whose waterfalls could have been used for power generation. But Câmara decided that rather than locating the iron works by the river banks, construction would begin on the slopes of the mountain as he believed that an existing canal from the Rio Picão to an old factory in the area could be used to transport the water necessary for the installation.

The scope of the installation initially conceived by Câmara was nothing short of grandiose: three blast furnaces and twelve refining furnaces built in such a way that the water flow used to power the former on a higher level could then be used to power the refining furnaces built on a lower location. The project was scaled down after the construction of the first blast furnace, one refining furnace and the hammer, when it became apparent that the water was insufficient for the original plant design.

After considerable difficulties encountered during the construction, a first attempt at smelting iron in the blast furnace is said to have failed in 1812 or 1813 for reasons that are not well clarified by Eschwege's account. What is certain is that later Câmara requested the government's assistance in enlisting the services of a German founder, Johann Schoenewolf, who had been working until then with Eschwege. Schoenewolf's reports to Eschwege provide a first hand account of events at the foundry.

The beginning of operations occurred on July 6th 1814 under Câmara's supervision. The founder's work was rendered difficult by the frequent breakdowns of the blasting equipment. Such breakdowns caused the temperature inside the furnace to fall unexpectedly so that the iron would not melt sufficiently and a great deal of effort was necessary to keep the iron flowing from the furnace. These problems came to a head on the evening of July 21st, when the cooling iron collecting in the hearth at the bottom of the furnace clogged the orifice through which it was meant to run. As a result of this accident, both the furnace lining and the blasting equipment were severely damaged. The repairs took a considerable amount of time and costs for the government, largely as a result of the incompetence of the director Câmara and his brother, who was later appointed to direct the work.[16]

While technical problems also plagued the operations of the forge hammer and the refining furnaces, a small output of bar iron was produced in 1815 partly by refining the pig iron obtained during the short period of operation of the blast furnace, and partly by refining blooms produced in two Swedish ovens. The latter were built in a belated attempt by Câmara to satisfy the government's expectations that bar iron be produced at the Fabrica. These Swedish furnaces were the primary source of output until 1820, when the blast furnace was finally ready to operate. Throughout, it appears that water shortages brought the iron works to a standstill, and so did the continuing dependence on foreign technicians and equipment that Câmara requested from the central government.

Meanwhile, Câmara continued to pursue expensive and grandiose modifications of the iron works, including three water reservoirs, a water tunnel and a canal for facilitating transportation of supplies and finished products to a navigable river, the Rio San Antonio. From there a new road link to the Rio Doce would have reduced the cost of transporting iron from Morro do Pilar to the ocean, thus enabling the export of iron from Morro do Pilar to the world markets.[17] Such extravagant plans brought the overall cost of the iron works at Morro do Pilar to 300,000 cruzados, a large figure considering the small output that the foundry could produce.[18] Schoenewolf concluded in 1815 that operating costs at the foundry were so high that the cost of bar iron had reached the staggering level of 12,800 reis per arroba. For the period 1815-1821, Eschwege estimates that bar iron from Morro do Pilar was sold on average for 2,000 reis per arroba while its average cost was 6,450 reis.

While detailed information on the operation of the Fabrica during the 1820s is lacking, historians and contemporaries agree that the project was a failure.[19] While Câmara linked his name to the operation of the first blast furnace in Brazil, the iron works at Morro do Pilar were shut down already in 1831, five years after its former director had been elected as senator.

Fabrica Patriotica do Prata (Congonhas do Campo)

Contrary to the previous two iron works, the last project reviewed here rejected the adoption of blast furnace technique and pursued the production of iron on a large scale through a different route. The promoter of the project was the German metallurgist Wilhelm-Ludwig von Eschwege who, after studying at the University of Gottingen, had entered the Portuguese Corps of Military Engineers since 1803, appointed by Jose' Bonifacio de Andrada e Silva. Upon his arrival in Brazil in 1808, Eschwege headed the Royal Service Commission of Minas Gerais and undertook a survey of the province's mineral resources.

In 1811, Eschwege developed a plan for an iron works in Minas Gerais. He described his motivations as the desire to be the first one to establish the production of iron on an industrial basis in Brazil. To this aim, he turned to Francisco de Assis Mascarenhas, Conde da Palma for help in securing financial support and governmental approval for a new iron foundry. Thus, in August 1811 a joint stock company was founded with a capital of 10,000 cruzados. Ten shares were assigned to nine partners, including Eschwege. The Fabrica Patriotica do Prata began operations at Congonhas do Campo in December 1812, although construction was completed fully in June 1813. The Fabrica consisted of four Swedish furnaces and two refining furnaces.

The technique chosen by Eschwege reflected his perception that blast furnaces were ill suited to the goal of producing for a small local market, and that the similarity between Swedish furnaces production techniques with the local technique of smelting *en cadinho* would have made it easier to train operatives for the forge. Eschwege is recognized to have introduced a number of technical innovations in the design of the iron works that were well adapted to the limited access to modern equipment. In particular, Eschwege designed a hydraulic apparatus (*trompas*) for blasting air into the furnace, avoiding the difficulties of installing water-powered bellows. This design was later adopted by other forges in the region, including the Fabrica Real at Morro do Pilar where the operation of the water-powered bellows had caused repeated problems. The government provided the foundry with a forge hammer and other equipment imported from England.

The Patriotica iron works were completed at a cost of 13,000 cruzados, considerably less than the investment at the other two plants. Moreover, the yearly iron output at Congonhas do Campo had exceeded repeatedly that of Morro do Pilar and come close to that at Ipanema. While the foundry's potential output was estimated at 4,000 arrobas per year, actual output barely exceeded 1,200 even after the doubling of the number of furnaces. Eschwege accounted for such limited output by reference to the lack of personnel and charcoal sufficient to run the furnaces day and night, as well as the lack of a demand for greater output. Thus, even after the number of Swedish furnaces was doubled, production occurred on only four furnaces at a time alternating between two sets of them every two or three days, because the efficiency of the process declined with the overheating of the furnaces after prolonged operation.

After Eschwege's return to Germany in 1821, the management of the foundry obtained poorer results as the consumption of charcoal per arroba of bar iron became five times as large. The fate of the forge is not entirely clear, as different sources suggest it to have shut down in the 1820s. Others claim it was still in operation in 1831.[20]

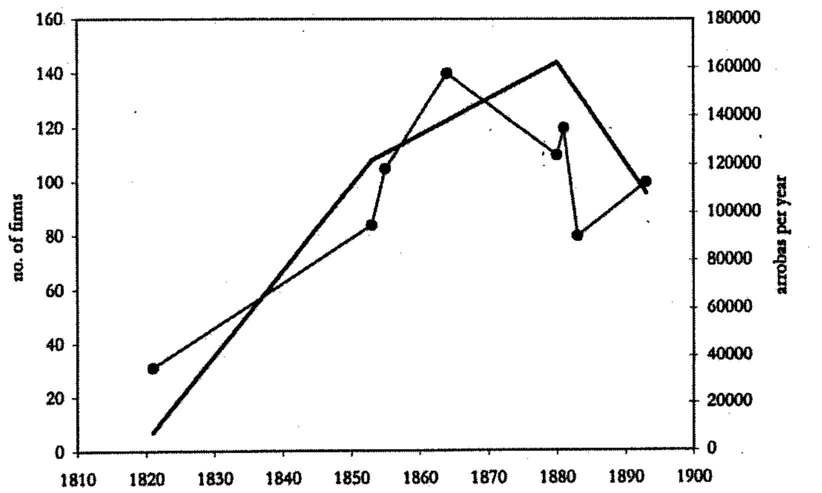
Output Trends, Industry Structure, and Technology During the Nineteenth-Century

The outcomes of these investment projects varied considerably, as did their influence on the further development of the industry. With the closing of the foundry at Morro do Pilar, Ipanema remained the only site where iron was produced with blast furnaces until the end of the century. On the other hand, the technique developed by Eschwege with small furnaces met with greater success and was replicated by other iron makers. More generally, variants of the direct method of production dominated the industry through the end of the century. Before discussing more specifically the evidence related to the spillover effects induced by the three large scale projects on the development of the industry, the latter's general characteristics will be reviewed here.

The available quantitative evidence on the development of the industry concerns the iron industry in the province of Minas Gerais, where a considerable fraction of the iron ore reserves of Brazil are concentrated.[21] These data (Figure 1) illustrate how the number of foundries increased from about thirty in 1821 to 140 in 1864, and decreased later on. Likewise, the available yearly output estimates for the years 1853, 1880, and 1893 indicate that the iron industry in Minas Gerais grew until the last few decades of the century when the arrival of the railroads into the province changed quite dramatically the impact of foreign competition on local iron makers.

It should be noted that Eschwege estimated the size of the provincial market for bar iron to be around 8,000 arrobas per year around 1820, a figure that together with Libby's implies an annual growth rate around 8.5% until mid-century.[22] This period of rapid growth was followed by a much more modest increase at less than 1% per year for the

Figure 1 - Active firms and total output in Minas Gerais



Source: Author's elaboration of data in Libby, Douglas, *Transformacao e Trabalho*, 1988.

next three decades, followed by a considerable decline until the end of the century. The growth of the industry during the first two thirds of the century had important implications for its structural characteristics.

Because of the modest size of the early century market for iron in Minas Gerais, Eschwege considered the development of large scale iron works to be economically unprofitable. Even if a doubling of the quantity demanded were associated to a 50% reduction in the local prices wrought by the substitution of local output for imported iron, a single factory operating one blast furnace and three refining furnaces would be sufficient to satisfy the whole market.[23] However, such an enterprise was unlikely to be profitable in light of the existence of numerous small foundries scattered around the province whose activity would reduce further the market for the output of a single large iron works. Only government policy could create the conditions for the latter to survive, for example by placing restrictions on the operation of foundries and forges.

Eschwege's comments ought to be qualified in light of his failure to foresee the subsequent increase in the size of the local market for iron which in principle should have created better opportunities for large scale iron works. But in spite of this fact, he was correct in considering the economics of iron making to favor relatively small establishments:

> From all that has been said, it follows without question that in Brazil no large iron factory will be able to remain profitable without a significant increase in the population. Only the small factories, distributed across all provinces, and with a maximum output of 2,000 arrobas per year, will turn better results.[24]

Eschwege's prediction is quite consistent with the estimates of the average output per foundry based on the data presented in Figure 1: 1,446 arrobas in 1853, 1,473 in 1880, and only 1,080 in 1893.[25] However, the industry structure by mid-century characterized by the coexistence of a few large establishments capable of producing as many as 18,000 arrobas per year, and a large fringe of smaller forges. The latter produced only a few hundred arrobas per year relying upon a minimal work force. While production activities at each of these establishments were typically short lived, new forges where iron was produced *en cadinho* were easy to set up at locations where iron makers could have access to the relevant natural resources.

According to surveys conducted in the 1870s and 1880s by engineers of the Escola de Minas established in Ouro Preto in 1875, the majority of the forges operated with the old technique of smelting *en cadinho*. Others employed Italian furnaces, a variant of the Catalan furnace for producing iron by the direct method. Data for twenty-two forges in Minas Gerais indicate an average annual output of 2,000 arrobas in the fifteen establishments smelting *en cadinho* and of 3,000 arrobas in the seven Italian forges.[26] The engineer Joaquim Candido da Costa Sena emphasized two problems.

The first was the still widespread practice of producing wood charcoal in pits, a process characterized by a very low yield of usable charcoal. Absent any regard for the need to manage the supply of wood, the high consumption of charcoal typical of the both the *cadinhos* and Italian furnaces led in many cases to the rapid deforestation of the areas surrounding the forges. In a few cases, the forges had been abandoned because of the lack of economical supplies of wood. The problem exposed by Sena in 1881 had been clearly in sight even earlier in the century. In 1832 the president of the province of Minas Gerais addressed the General Council advocating the regulation of iron production in light of the destruction of the woods in areas very close to the population.[27]

A second problem emphasized by Sena concerned the lack of technically competent personnel to operate furnaces and other equipment. This fact was held to be responsible for the adoption of *cadinhos* in locations where superior Italian or Catalan furnaces could have been established. Sena, like several of his contemporaries, attributed the primitive state of the techniques used in iron production to the forge owners' extensive reliance on an unskilled slave workforce. But the link between the employment of slave labor and the industry's failure to adopt superior techniques is not at all obvious. Several nineteenth century discussions explained that link in terms of the limits to the slaves' learning capacity. In the next section, the nature of the technological learning processes at work in the industry will be examined in greater detail and a different explanation for the lacking accumulation of capabilities will be proposed.

Technological Spillovers and Accumulation of Capabilities in a Slave Economy

The limited state of development of the iron industry toward the end of the nineteenth century supports the conclusion that no accumulation of technological capabilities occurred over the course of the century.[28] In light of the stimulus that the government gave to the development of local iron production early in the century, the central goal of this section of the paper is to investigate the reasons why the employment of foreign metallurgists and technicians at the three large scale foundries failed to trigger a self-sustaining process of technological learning. Baer attributes the stalled development of the local iron industry to the lack of leadership after the departure from Brazil of these foreign pioneers.[29] Such a statement obscures the importance of structural impediments among which the limited development of an economical transportation system and of a large industrial market for iron products is perhaps the most important.[30] Even then, the iron industry experienced a considerable quantitative growth, although it did so in the absence of a significant and lasting upgrading of the dominant production techniques. The historical evidence presented here is directly concerned with this phenomenon.

The three projects reviewed above contributed to the development of the iron industry early in the century. The spillovers occurred through the dissemination of useful technical information and the migration of individuals who, having worked at these establishments, carried their newly acquired capabilities into existing or new iron works.

Among such individuals, the most prominent is certainly the engineer Jean Antoine de Monlevade, a Brazilian who studied in Paris where he graduated from the Ecole Polytechnique in 1809. Upon his return to Brazil, Monlevade spent a few years working with Eschwege at Congonhas do Campo before striking out on his own. In 1818, Monlevade formed a partnership with a Captain Louis Soares de Gouveia in order to build a blast furnace in Caete. This works is said to have started production in 1818, operating intermittently because of the lack of charcoal until 1822.[31] Subsequently, Monlevade acquired some land adjacent to the Rio Piracicaba and established a new foundry based on Catalan furnaces. In 1823 the Fabrica Solar began producing and became the largest iron works in Minas Gerais, and probably all of Brazil through much of the century. Archival records indicate that 151 slaves (including 95 adult men) worked at the fazenda owned by Monlevade in 1840.[32] At his death in 1872, his estate included 250 slaves, a fairly large labor force that participated in a range of productive activities at the fazenda, including iron making. In 1853 Monlevade produced an output of about 18,000 arrobas, a scale comparable to that achieved earlier on at the Ipanema foundry. His iron products were sold throughout Minas Gerais, and also in parts of the province of Sao Paulo where competition from imports was stronger.

In response to Camara's request for skilled personnel to replace Schoenewolf, the departing furnace master, the government recruited in 1820 a number of German technicians for employment at the two foundries in Ipanema and Morro do Pilar.[33] The team headed for Morro do Pilar included Hermann Utsch and his son Johannes Heinrich whom the Brazilian government employed for ten years at Morro do Pilar as furnace master and furnace hand for an annual compensation of 900 and 400 cruzados respectively, plus various benefits typically awarded to foreign personnel. Another assistant to the furnace master, Carlos Hamlott, was sent to Morro do Pilar in 1828. Shortly after the closing of the foundry in 1831, the government invited Hermann Utsch to work at

Ipanema for three years. Utsch requested that his three sons also be hired at the Fabrica. While this request was denied, in 1834 the government offered an annual compensation of 1,250 cruzados to the eldest son Johannes Heinrich for him to train personnel at Ipanema.[34]

Shortly after the closure of the Fabrica at Morro do Pilar, the Utsch father and son established a new forge in Sumidouro, a small village near Conceição. According to family sources, the yearly output of the factory exceeded 5,000 arrobas of bar iron used to produce tools such as sickles and shovels. While this output level would indicate that it was at one point a sizeable enterprises, it had stopped operating by the late 1870s when Sena found it inactive as the surrounding forest had been depleted.

The activities undertaken by Eschwege in the province of Minas Gerais and particularly his work at the Fabrica Patriotica at Congonhas do Campo were another important source of spillovers for the local iron industry. Eschwege's technical competence was instrumental to the adoption of the water-powered hammer first in the forges at Girau, founded in 1808 by Capitao Paulo Jose' de Souza and Joao Mota Ribeiro under royal charter. The German scientist visited the Girau works in Itabira (Minas Gerais) in 1811, and provided the technical specifications for building a forge hammer. Thanks to his technical advice and the assistance of a technician sent over to help with the installation, Girau became the first iron works to use waterpower in this stage of the refining process. Later on, four other people imitated the analogous installation at Congonhas do Campo and in a short time already sixteen additional forges had adopted the innovation.[35]

Many other iron works set up during the first two decades of the century benefited from Eschwege's technical advice or his direct involvement. Archival sources indicate that Eschwege participated in the establishment of an additional five forges, whose direction was then entrusted to others.[36] Other iron producers benefited from the possibility to send their master carpenters to Congonhas do Campo in order to examine and imitate features of Eschwege's own forge. Interestingly, Eschwege mentions the existence of entrepreneurs who not willing to be seen asking for his help would nonetheless proceed with design and construction plans clearly inspired by the Fabrica Patriotica. These entrepreneurs' failure to avail themselves of Eschwege's collaboration was occasionally the cause of design problems that could have been easily avoided.

This evidence suggests that the activities of the three large scale projects and of several individuals associated with them did have technological spillovers in the region. It also bears witness to the crucial role played by the government in the first three decades of the century, particularly in harnessing the technological capabilities of foreign technicians to the start-up of the three enterprises. Likewise, recognition of the need to train local personnel played an important role in the recruitment of foreign technicians and their placement at the three foundries. Already in 1823 the government had discussed the idea of establishing a mining school in Minas Gerais. A law approving the creation of a course in mining engineering was passed in 1832, although its mandate was never executed until 1875.[37] This delay is symptomatic of the fact that government support to the development of the iron industry stalled in the 1830s. In the absence of government action to that effect, the immigration of foreign personnel came to a halt. As seen earlier, the cost of recruiting European technicians was considerable and likely out of the financial possibilities of all but the large scale enterprises, such as those funded by the government.

As the inflow of new technically competent personnel came to a halt, the process of technological learning in the industry came to depend much more strongly on the acquisition of capabilities through either formal or informal training, as well as through on-the-job learning. It is well known that skills in the various tasks required for the operation of a foundry or a forge were typically acquired as a result of learning-by-doing. On these grounds, it can be argued that the development of technological capabilities and their diffusion among firms in the industry were linked in a crucial way to the training of personnel on the job and the patterns of workforce mobility and interaction among firms. Eschwege's discussion of operations at his own Fabrica provides very interesting observations in this regard.

In fact, a major difficulty in the operation of the forge was related to his inability to retain skilled workers to whom crucial tasks could be reliably delegated. In spite of his initial reluctance to acquire slaves for operating the works, experience taught Eschwege that free workers would want to leave from the firm as soon as they had completed a sufficiently long apprenticeship with the German iron masters. Attempting to hold them to their contractual obligation was hardly a promising strategy considering the vagaries of legal enforcement in Brazil and the impossibility to hold workers to adequate standards of performance. Likewise, hired slaves were almost inevitably withdrawn from service by their owners who would exploit their slaves' newly received training by entering into iron production themselves. Thus, Eschwege realized that by refusing to acquire slaves of his own, the factory would have been forever involved in training new apprentices.

From Eschwege's own account, only two of thirty free workers who received their training at the Fabrica Patriotica were retained, partly as a result of a generous pay raises. Absent more detailed information about the extent of the flows of labor among productive units, we can only speculate that this external effect must have been weakened substantially as soon as Eschwege began using exclusively owned slaves.

The labor management problems encountered at Congonhas do Campo, and their resolution through the recourse to owned slaves, plagued also the operations of the foundry at Morro do Pilar and must have been quite typical among enterprises in the iron industry across the country. Libby documents thoroughly the pervasive dependence on slave labor for most iron works in Minas Gerais until the abolition of slavery in 1888.[38] The implications of this phenomenon have to be considered in light of the fact that the high costs of recruitment of foreign skilled workers provided a strong inducement to the training of slave labor for skilled work in the foundries and forges.

Indeed, it appears that the Fabrica Patriotica itself, admittedly among the most technologically sophisticated firms, was operating with 20 slaves and only three free men in 1820. A similar situation prevailed across the range of enterprises in operation at different times during the century.[39] The use of slave labor was not at all confined to the enterprises that smelted iron *en cadinho* on a very small scale. Even Monlevade, whose firm is considered the largest and most advanced iron works by the third decade of the century, relied almost entirely on slave labor. Furthermore, slave labor was used for most tasks in the division of labor at the nineteenth century iron works, regardless of their skill content. It is necessary therefore to consider whether or not the industry wide reliance on slave labor can provide us with an explanation for the lagging diffusion of advanced production technique in the Brazilian iron industry.[40]

Our evaluation of the historical evidence is that the explanation cannot be cast in these terms. This assertion is based on the observation that even Monlevade's iron forge, the most advanced private iron works during the 1830-1880 period, relied entirely on owned slave labor. The engineers at the Escola de Minas noted that Monlevade was the only iron maker who had adopted the Catalan method, one that required a considerably more skilled work force and a more sophisticated organization. The fact that Monlevade succeeded in conducting a Catalan forge for many years while employing his own slaves was attributed to Monlevade's own competence and continuous involvement in the direction of the operations, as well as to his commitment to training his work force. In his 1853 report to the provincial government on the state of his iron works, Monlevade emphasized the availability of 150 slaves trained in the art of iron-making, in the production of wood charcoal according to European techniques (kilns), and in the molding of iron of all shapes and sizes.

It has to be noted that in spite of Monlevade's emphasis on training workers, there are reasons to believe that the direction of work at the forge was firmly in his hands. Thus, when the forge had to be reorganized after his death in 1872, a new forge master had to be recruited. The firm could not find any individual who could continue operations of a Catalan forge. As a result, the new forge master converted the furnace to the simpler Italian method.[41]

It is not possible to determine on the basis of the existing evidence why the need for a new forge master could not be filled internally. Yet, the difficulty in recruiting a forge master skilled in the Catalan method is revealing of the thinness of the market for skilled labor. An Italian forge located around Santa Barbara was found inactive and abandoned by the engineer Armand de Bovet in the early 1880s. The reason for this forge's shutdown was that no replacement could be found for the slave forge master at his death.[42]

The implication of this evidence appears to be that the introduction of techniques for iron production more advanced than that based on the *cadinhos* was compatible with the continuing reliance on slave labor. It should be emphasized that on-the-job experience under one method of iron production could hardly be the base for mastering the organization of work under a more complex method. The introduction of superior techniques was therefore a decision that forge owners had to make. Hence, the owners' lack of technical knowledge is a more plausible causal explanation for the continuing reliance on the *cadinho* technique. Nor could the skills needed to operate a forge based on more advanced technique be easily acquired by hiring a forge master locally. The supply of skilled labor was significantly restricted as a result of the practice of retaining owned slaves.

The importance of formal training programs aimed at the creation of a pool of skilled workers was emphasized in Monlevade's considerations regarding the possibility to undertake the large scale production of pig iron in Minas Gerais. In his 1853 report to the provincial government, Monlevade listed as the first condition the creation of a school for the teaching of metallurgy and iron making techniques.[43]

The proposition advanced here is that the reliance on slave labor per se was not a critical impediment to the introduction of techniques more advanced than the use of *cadinhos*. This point can draw further validation by a brief examination of the techniques for iron production prevalent in the U.S. iron industry since the mid-eighteenth century where producers also made extensive use of slave labor or indentured servants.

In Pennsylvania, for example, where the iron industry development began in the early eighteenth century, forty-one cold-blast furnaces were in operation in 1800, producing an average output of 530 tons of pig iron.[44] Firms in the industry relied upon slaves and indentured servants not only for unskilled and semi-skilled work, including woodcutters, stockers, and assistants to founders and forgemen, but also for skilled work. The high cost of free skilled labor, often foreign founders and forge men whose relocation costs had to be borne by the hiring firms, and their frequent lack of work discipline induced iron masters to attempt whenever possible to train skilled forge men and founders among their own slaves. Success in this endeavor and the reduced need for hired hands in the most skilled tasks was perceived as critical to the profitability of the enterprise.

Charles Dew's study of the iron making business owned by William Weaver in Virginia provides a detailed account of this firm's labor management practices.[45] In the 1850s Weaver's Buffalo Forge – where pig iron was refined into anchonies and bar iron – was entirely staffed by owned slaves. This situation was the result of their long tenure with their master, and a deliberate effort on the latter's part to train them into highly skilled operatives in order to reduce the business dependence on the uncertainties of the slave labor market, and on the need to hire skilled free labor and skilled slave labor alike. Iron makers like Weaver were also aware of the fact that their reliance on learning-by-doing and the in-house training of apprentices by current masters limited the scope of productivity improvements that could be realized. The state of relative isolation in which slave labor at a foundry or forge operated precluded the inward diffusion of technical improvements from outside without the active direction and involvement of the iron works owner or manager. In a 1812 letter to a clerk, David Ross, owner of the Oxford Iron Works in Virginia, expressed these limits by noting of his slave workers that "*they are good people but have never seen any other workmen than at the Oxford estate—they have no chance for improvement—there is no emulation—the father and son joggs on in the old way.*"[46]

In conclusion, it can be argued that the employment patterns found in the Brazilian forges and foundries were not qualitatively dissimilar from those in the U.S. Furthermore, both Brazilian and U.S. scholarship supports the position that slave labor could, and was routinely relied upon for skilled work as well as unskilled work in the iron industry, with the possible exception of the management of the establishment itself, a role usually covered by a free agent of the owner or the owner himself. The widespread diffusion of blast furnace technology in the U.S. firms provides additional strength to the argument that the lagging technological sophistication of the iron industry cannot be attributed to the dominant use of slaves.

Conclusion

The Brazilian government's support of the establishment of modern iron works was not sufficient to trigger an autonomous process of technological learning in the industry. The need for a source of technical knowledge alternative to the recruitment of foreign founders and forge specialists was acknowledged in the 1832 law authorizing the creation of a school on the model of institutions like the *Ecole des Mines* in France. Unfortunately, the government did not act accordingly until much later, so that the Escola de Minas in Ouro Preto only began instruction in 1876. At the same time, a strong commitment to the systematic training of skilled iron workers was absent from most establishments, that consequently lacked even the ability to maintain their own standards of technical efficiency when confronted with rather foreseeable events, like the death or departure of skilled personnel.

The weakness of the indigenous capabilities accumulated over the course of the nineteenth century contributed to the decline of the iron industry that followed the construction of a railroad network and the abolition of slavery toward the end of the century. In spite of the founding in 1875 of the Escola de Minas in Ouro Preto, the domestic industry could hardly withstand the competition from imported iron and steel. While advanced economies were witnessing the advent of integrated steel mills in an industry that had become dominated by large scale corporations, a team of four entrepreneurs were hard at work setting up the Usina Esperança at Itabirito. In 1889, Brazil's third blast furnace iron works began operating.

Notes

1. I am grateful to Douglas Libby, João Antônio de Paula, Larry Malone, two anonymous referees, and participants at the Economic and Business Historical Society 2003 conference in Memphis for their helpful comments and suggestions.

2. Gale, W.K.V., *Iron and Steel* (Harlow, UK: Longmans, 1969); Schubert, H.R., "Extraction and Production of Metals: Iron and Steel," in *A History of Technology*, ed. Charles Singer, et al. (Oxford: Clarendon Press, 1964), 99-117.

3. Baer, Werner, *The Development of the Brazilian Steel Industry* (Nashville, TN: Vanderbilt University Press, 1969).

4. It is worth noting that Portugal had been excluded from much of the intellectual ferment behind the advances of the scientific method at least up until the mid-eighteenth century, as the control of educational institutions was largely in the hands of the Jesuits. Only then, an attempt at reforming the nature of instruction began under the direction of the Marquis de Pombal. While not entirely successful, the Pombal reform provided the Portuguese with a reformed Universidade de Coimbra, providing a significant impulse to the study of sciences and the application of scientific knowledge to practical problem. See the discussion of these events in: Schwartzman, Simon, *A Space for Science* (University Park: Pennsylvania State University Press, 1991); and Azevedo, Fernando de, *Brazilian Culture* (New York: Macmillan, 1950).

5. Azevedo, Fernando de, *As Ciencias no Brasil, Vol. I.* (São Paulo: Editora Melhoramentos, 1955).

6. Pinto, Manuel Serrano, "Aspectos da Historia da Mineracao no Brasil Colonial," in *Brasil 500 Anos – A Construcao do Brasil e da America Latina pela Mineracao*, ed. F.A. Freitas Lins, et al. (Rio de Janeiro: CETEM, 2000), 27-44.

7. The location of the plant was chosen such as to exploit the ores of magnetite of the Morro de Aracoiaba. Bain and Read characterize these ores as difficult to work with because of the high content of phosphorus and titanium. See: Bain, H. Foster, and Thomas Thornton Read, *Ores and Industry in South America* (New York: Harper, 1934).

8. The Swedish furnace is a different nomenclature for the *stückofen*. This is a furnace that appeared in different regions of Europe during the late medieval period, after attempts were made to increase the size of the Catalan furnaces originating from Spain. See Dennis, W.H., *Foundations of Iron and Steel Metallurgy* (London: Elsevier Publishing, 1967); and Sass, Stephen L., *The Substance of Civilization* (New York: Arcade Publishing, 1998).

9. The arroba is a unit of weight equivalent to about 32 lbs, so the proposed output is about 560 tons.

10. Eschwege, Wilhelm Ludwig von, *Pluto Brasiliensis, 2° Volume* (São Paulo: Livraria Itatiaia Editora, 1979).

11. Spix, Johann Baptist von, and Carl Friedrich Philipp von Martius, *Viagem pelo Brasil, Volume I* (São Paulo: Editora Melhoramentos, 1955).

12. Eschwege, *Pluto Brasiliensis*, 229.

13. Spix and Martius, *Viagem, Vol. I*, 170.

14. Eschwege, *Pluto Brasiliensis*, 240.

15. Baer, *The Development of the Brazilian Steel Industry*, 52.

16. Eschwege, *Pluto Brasiliensis*, 210.

17. Eschwege, *Pluto Brasiliensis*, 212; Spix and Martius, *Viagem pelo Brasil, Volume II* (São Paulo: Editora Melhoramentos, 1955), 21.

18. Spix and Martius report that Ferreira defended himself from the heated criticism of many by reimbursing the government of all costs incurred, an amount of money that the two estimated at 200,000 cruzados. However, Eschwege claims that the government rejected the offer. See: Spix and Martius, *Viagem, Vol. II*, 21; and Eschwege, *Pluto Brasiliensis*, 260.

19. Baer, *The Development of the Brazilian Steel Industry*, 51; Ramos, Jose' Raymundo Andrade, "Mineracao no Brasil Pos-Colonia," in *Brasil 500 Anos – A Construcao do Brasil e da America Latina pela Mineracao* ed. F.A. Freitas Lins, et al. (Rio de Janeiro: CETEM, 2000), 59-64; Eschwege, Wilhelm Ludwig von, *Jornal do Brasil, 1811-1817* (Belo Horizonte: Fundacao Joao Pinheiro, 2002), 174-175; Spix and Martius, *Viagem, Vol.II*, 21.

20. Libby, Douglas C., *Transformacao e Trabalho em una Economia Escravista: Minas Gerais no Seculo XIX* (São Paulo: Brasiliense, 1988), 139.

21. Libby, *Transformacao e Trabalho*, 154. Libby's estimates are based on nineteenth century writings complemented by his own study of archival data.

22. Eschwege, *Pluto Brasiliensis*, 259; Eschwege, *Jornal do Brasil*, 176.

23. Scrivenor indicates that in Britain charcoal-based blast furnaces produced an average output of about 38,000 arrobas in 1788. See Scrivenor, Harry, *History of the Iron Trade* (New York: A.M. Kelley, 1968). Varnhagen hoped to be able to produce at Ipanema at a daily rate of 120 arrobas, or more than 40,000 arrobas per year.

24. Eschwege, *Pluto Brasiliensis*, 261 (author's translation).

25. These estimates are based on the output data in tons from Libby, *Transformacao e Trabalho*, 154. Tons are converted into arrobas according to the old Brazilian measuring system (1 ton = 54 arrobas). If Libby's data are assumed to be in Imperial tons, the arrobas equivalent is 71 units and average output per foundry would be very close to 2,000 arrobas.

26. Sena, Joaquim Candido da Costa, "Viagem de Estudos Metallurgicos no Centro da Provincia de Minas," in *Annaes da Escola de Minas*, 1 (1881): 106-143.

27. Baeta, Nilton, *A Industria Siderurgica em Minas Gerais* (Belo Horizonte: Imprensa Oficial, 1973), 177.

28. Calogeras, João Pandiá, *As Minas do Brasil e Sua Legislação – Vol..II,* (Rio de Janeiro: Imprensa Nacional, 1905), 103.

29. Baer, *The Development of the Brazilian Steel Industry*, 54.

30. Paula, João Antonio de, "A Siderurgia em Minas Gerais – 1809-1888," in *II Seminario Sobre a Economia Mineira*, ed. Haydn Coutinho Pimenta (Belo Horizonte: CEDEPLAR, 1983), 24-31.

31. Baer, *The Development of the Brazilian Steel Industry*, 54; Passos, Juliana Ma. do Nascimento, *Monlevade, Vida e Obra* (Belo Horizonte: Associação Monlevade, 1973), 30-31.

32. Libby, *Transformacao e Trabalho*, 166; Birchal, Sergio de Oliveira, "O Empresario Brasileiro: Um Estudo Comparativo," in *Revista de Economia Politica*, 18, no.3 (July-September 1998): 16-37; Birchal, Sergio de Oliveira, 1999. *O Mercado de Trabalho Mineiro no Seculo XIX*, manuscript.

33. Eschwege, *Jornal do Brasil*, 175.

34. Baeta, *A Industria Siderurgica*, 156-157.

35. Eschwege, *Jornal do Brasil*, 173.

36. Baeta, *A Industria Siderurgica*, 207.

37. Carvalho, José Murilo de, *A Escola de Minas: O Peso da Gloria* (Belo Horizonte: Editora UFMG, 2002), 17.

38. Libby, *Transformacao e Trabalho*, 160-178.

39. Libby, *Transformacao e Trabalho*, 160-170.

40. Affonso de Paula, Ricardo Zimbrao, *Industria em Minas Gerais: Origem e Desenvovimento*, paper presented at X Seminario sobre a Economia Mineira, CEDEPLAR, Universidade Federal de Minas Gerais, 2002.

41. Bovet, Armand de, "A Industria Mineral na Provincia de Minas Gerais – Primeira Parte," in *Annaes da Escola de Minas*, 2 (1883): 4-99.

42. Ibid., 48.

43. Passos, *Monlevade*, 79.

44. Paskoff, Paul F., *Industrial Evolution: Organization, Structure, and Growth of the Pennsylvania Iron Industry, 1750-1860* (Baltimore: The Johns Hopkins University Press, 1983).

45. Dew, Charles B., *Bond of Iron: Master and Slave at Buffalo Forge* (New York: W.W.Norton & Co., 1994).

46. Dew, Charles B., "David Ross and the Oxford Iron Works: A Study of Industrial Slavery in the Early Nineteenth-Century South," *The William and Mary Quarterly*, 3rd Series, 31, no.2 (April 1974): 189-224, 216.