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Competition and the Value of Innovation

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Cyanide on the Rand: Competing Methods of Technology Transfer ^{*}

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Abstract

We study technology diffusion mechanisms using a unique historical setting: the introduction of the cyanide method of gold extraction on the Witwatersrand goldfields in the late 19th and early 20th centuries. Mines managed by the same mining house were more likely to adopt the new process, which increased extraction rates by around 50%. Cyanide technology was continually improved after its introduction. We find evidence of knowledge spillovers from engineers and mine managers but not white-collar employees. Geographical spillovers are extremely localized in nature.

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1 Introduction

The diffusion of new technology is fundamental to productivity gains and economic growth. However, linking the diffusion of technology to productivity improvement is difficult, largely due to data availability. In addition, the knowledge spillover literature usually focuses on one single spillover mechanism without conditioning on other potential channels and the knowledge about which mechanism is the most effective in achieving productivity gains and economic growth. This paper tests the effectiveness of multiple knowledge spillover mechanisms in improving productivity. Understanding the most efficient knowledge spillover mechanism could help policymakers to allocate resources better to incentivize innovative activities and facilitate technology spillovers.

Nonetheless, answering this question empirically is challenging for several reasons. First, the well-documented product market rivalry effect could confound the observed technology spillovers (Bloom et al., 2013a). Next, technology adoption decisions and the productivity associated with the new technology are rarely observable by researchers. Even if they are observable, multi-location multi-segment businesses will make identifying technology spillovers troublesome.

We investigate how technology was transferred in an environment that overcomes these empirical challenges: the South African goldfields when the cyanide method was introduced. There are several benefits of studying technology diffusion in our setting. First, we eliminate product market rivalry incentives due to the operation of the Gold Standard. The price of the firms' output, gold, was fixed during this period. Firms could deliver as much gold as they produced to the world's central banks and receive a fixed, nominal price per ounce. Second, we avoid the issue of equating patenting with innovation. We measure changes in mine productivity in a precise fashion, how much gold could be extracted from a tonne of ore. Third, we avoid measurement issues, such as multi-product (and multi-industry) firms which are present in studies such as Jaffe (1986). The firms in our sample mined ore and extracted gold from the ore at a single physical location and had virtually no other operations. These single-plant, single-product firms allow us to avoid the problem of the 'scarcity of directly observable measures of technological innovation' (see Kogan et al., 2017). A final advantage is the relatively high-frequency data that we possess. We observe firm-level productivity at monthly frequency, rather than the annual frequency used by studies such as Bloom et al. (2013b). Our setting is useful as it allows us to distinguish between different methods of technology transfer – physical proximity, organizational affiliation, key personnel, and common national origins of shareholders.

We observe monthly production data for 116 mines from 1887 to 1907. For each mine we compile data on the tonnes of ore mined, the ounces of gold extracted by traditional and cyanide

processes, and key personnel, both operational and administrative. We observe the distance, as the crow flies, between any pair of mines. If physical proximity is critical, then closer mines should experience faster technology transfers than more distant mines. Our study of physical proximity in mining allows us to avoid the problem of agglomeration effects. Gold mines did not locate next to each other to enjoy access to a ‘cheaper and faster supply of intermediate goods and services, proximity to workers or consumers, or a better quality of worker-firm matches (see [Greenstone et al., 2010](#), p. 537). Instead gold mines located where profitable ore was discovered. As each tonne of ore contained only a few ounces of gold, treatment of the ore occurred at the surface above the mine. Therefore, firm distance is effectively exogenous with respect to the level of technology employed by the mine.¹

Theoretical prediction:[What’s the theoretical prediction or existing evidence on spillover mechanisms?]

Organization: Financial/technical support vs. Crowding-out

White-collar workers could also facilitate the transfer of cyanide knowledge. Breakthrough technology might require major changes in the organizational forms ([Juhász et al., 2021](#)), in which the management team typically takes a critical role. In addition, directors can bring in knowledge about better management practices ([Giannetti et al., 2015](#)) and the existence of common venture capital investors could also help improve innovation efficiency through exchanging innovation resources. There is also anecdotal evidence that suggests that the board of directors can also influence the decision-making process of mines’ daily operations. For example, some mines reported that “the directors had decided to adopt a method of selecting the ore” and “the directors have decided to increase the stamping power to 80 heads”. Therefore, it is plausible that directors also engaged in the decision-making process of adopting and perfecting the use of the cyanide method.

Geographical:

Empirical Design: To capture the knowledge spillover effects, we test whether and by how much a focal mine’s cyanide productivity improves after connected mines experience increases in their cyanide productivity, controlling for the focal mines’ characteristics. First, we measure cyanide productivity as the proportion of gold that can be recovered by the cyanide method out of all recoverable gold left in the ore after mercury amalgamation, the first stage treatment. Then, we construct a measure that captures cyanide knowledge a focal mine can learn from each potential mechanism. The cyanide knowledge pool is a connection intensity weighted sum of connected mines’ abnormal cyanide productivity in the previous period. Two mines were

¹Firms’ locations were effectively fixed, however, variation in the distance to competitors was determined at the extensive margin. Unproductive mines could shut down and productive mines could open.

connected if they are (1) located within 5 kilometers, (2) affiliated to the same mining house, or (3) share common personnel.

To further alleviate the concern that ore quality would directly affect cyanide productivity, we include mine fixed effect and the accumulated tonnage of treated ore to account for the ore quality difference due to a mine’s surface location and depth. We also include month fixed effects to control for seasonal effects, for example drought and flood, that could simultaneously affect multiple mines’ cyanide productivity.

Main Findings: We observe key personnel: mine managers, engineers, directors, and company secretaries. Part of the managers’ and engineers’ roles were to improve the technical efficiency of extracting gold from its ore and to reduce the costs of doing so. We find strong evidence that ‘hands-on’ personnel successfully transferred knowledge of the cyanide process between mines. In contrast, we find no evidence that white-collar personnel were effective, by themselves, in transferring technical knowledge in contrast to the results of [Baum et al. \(2022\)](#). However, entrepreneurs and directors were critical in organizing mines within a mining house. Therefore organizations were indirectly responsible, via appointing common engineers and managers to multiple mines at the same time, for the spread of innovation.

We find evidence that physical proximity and operational personnel were effective in diffusing knowledge of the recently invented cyanide process for extracting gold from its ore. In contrast, mines with common ownership (and associated organizational structures) and white-collar employees, such as directors and company secretaries, played a less important role. There is also little evidence that knowledge flowed more easily when there was a common national origin of firms’ shareholders.

It is possible that the positive dynamic correlation between a mine’s own productivity and other connected mines’ productivity could be driven by forces other than knowledge spillovers. There could be spatially correlated productivity shocks, for example, weather conditions, soil/ore quality, and labour supply. However, this is not a major concern in our setting. First, gold mine productivity is not obviously weather dependent. In events of extreme weather, like floods, mines would choose to shut down if the weather affected their production. In addition, unlike soil conditions which can change from year to year, ore quality was set exogenously millions of years ago. Therefore, the observed positive correlation between two geographically closed mines is unlikely to be driven by spatially correlated productivity shocks. Last, all our mines are located in a 60-kilometre range and workers are highly mobile within the region, which means the supply shocks of skilled labour would be captured by the month fixed effects and are unlikely to affect mine productivity differently.

Contribution:[Related to AE’s point 4] [maybe mention some specific sectors: for example, open source code and academia.]

Maybe a separate theory / hypotheses? [What’s the theoretical prediction or existing evidence on spillover mechanisms?]

Spillovers are by no means guaranteed. For example, [Bloom et al. \(2013a\)](#) find that only 2% of neighbouring firms learned any details of improved management practices in an experiment on Indian textile firms. They speculate that textile firm managers were reluctant to pass on information to rival firms who might be tempted to poach key personnel. The lack of vigorous inter-firm competition in South African gold mining make our results (of sharply declining spillovers with distance) even more striking. Mining firms did not have to worry about market competition effects (see e.g., [Bloom et al., 2013b](#)) as firms acted cooperatively for political and economic reasons. The Chamber of Mines opposed increases in taxation and advocated better conditions for European capital from the Transvaal Republic. Most mines jointly hired unskilled labour through the Witwatersrand Native Labour Association and technical knowledge was shared via the Chemical and Metallurgical Society.² The absence of ‘market stealing’ effects meant that firms in the same mining house, with their different shareholders, may have been unlikely to object to operational knowledge being transferred to other firms. Our results, of co-operative behavior between mines, stands in contrast to the noncooperative behavior found in U.S. oil and gas drilling, see [Hendricks and Porter \(1996\)](#) and [Lin \(2013\)](#).

Maybe a separate literature review?

Many studies have found that physical proximity aids knowledge transfer (e.g., [Audretsch and Feldman, 1996](#); [Glaeser et al., 1992](#); [Jaffe and Adams, 1996](#); [Jaffe et al., 1993](#); [Marshall, 1890](#); [Porter, 1990](#)). However, the literature is divided on how distance affects knowledge spillovers. Some find that spillovers occur at the country level (e.g., [Fischer et al., 2006](#); [Greenstone et al., 2010](#); [Singh, 2007](#)). Others document spillovers at the city or regional level (e.g., [Glaeser et al., 1992](#); [Porter, 1990](#)). In contrast, we find little effect of spillovers at distances over two and a half kilometres. Our results differ from those of [Lychagin et al. \(2016\)](#) and [Orlando \(2004\)](#) who find little attenuation of knowledge diffusion by distance. Even firms that produced an identical product, and used virtually the same technology, show drastic decreases in knowledge spillovers even at very short distances.

Knowledge spillovers may occur at the individual, rather than the corporate, level. [Pogue \(2006\)](#) argues that South African mining engineers and metallurgists in this era formed a ‘localized knowledge network’ that aided the diffusion of the cyanide technique. [Lychagin et al.](#)

²Commonly known as the ‘Cyanide Club’, see [Pogue \(2006\)](#) p. 82

(2016) show that inventor locations, not corporate headquarters, matter for knowledge transfers. Conley and Udry (2010) document information flows, such as how much fertilizer to apply, occurs between individual Ghanaian pineapple farmers. They find that farmers who performed well above, or below, expectations provided the most useful information to their peers. In contrast, Borjas and Doran (2012) and Waldinger (2012) find little evidence of knowledge spillovers at the personal level.

Technology diffusion within an organization often occurs (see e.g., González-Uribe, 2020; Liu, 2008)). Yet the organizational environment is important, and some organizations may lack the comfort or power to successfully transfer knowledge, even if the ability exists (see Cohen and Levinthal, 1989; Levin, 1999)). Most mining companies were members of a mining ‘house’ (e.g., Consolidated Goldfields of South Africa, A. Goerz and Company, Rand Mines). Mining houses had been established by early South African entrepreneurs such as Hermann Eckstein, Joseph Robinson, and the Albu brothers. The mining houses were large shareholders in the operating mines and provided technical and administrative support (see Martin, 1929). If common ownership is important to facilitate technology dissemination, mines within the same mining house should experience faster transfers than unaffiliated mines. We document that mining houses had some ability to transfer knowledge between their constituent firms. However, mining companies within a mining house rarely merged or transferred assets between each other. Therefore, the channels illustrated by González-Uribe (2020): carve-outs, spawning, and recycling, do not appear to be necessary conditions to enable information flows within an organization. Instead, mining houses appointed managers and consulting engineers to multiple mines within the ‘house’ to spread knowledge.

Old Introduction

A large literature documents the channels through which technology is transferred. We investigate knowledge spillovers that may arise due to physical proximity, organizational hierarchies, key personnel, or common national origins of shareholders in the South African gold mining industry. Gold was first mined near Johannesburg in 1886, and South Africa was the world’s largest gold producer for most of the 20th century. The first commercial technique to extract gold from its ore with cyanide began on these goldfields in 1890. We examine South African gold production from 1887 until 1907.

There are several benefits of studying technology diffusion in our setting. First, we eliminate product market rivalry incentives due to the operation of the Gold Standard. The price of the firms’ output, gold, was fixed during this period. Firms could deliver as much gold as they produced to the world’s central banks and receive a fixed, nominal price per ounce. Second, we avoid the issue of equating patenting with innovation. We measure changes in mine productivity in a precise fashion, how much gold could be extracted from a tonne of ore. Third, we avoid measurement issues, such as multi-product (and multi-industry) firms which are present in studies such as [Jaffe \(1986\)](#). The firms in our sample mined ore and extracted gold from the ore at a single physical location and had virtually no other operations. These single-plant, single-product firms allow us to avoid the problem of the ‘scarcity of directly observable measures of technological innovation’ (see [Kogan et al., 2017](#)). A final advantage is the relatively high-frequency data that we possess. We observe firm-level productivity at monthly frequency, rather than the annual frequency used by studies such as [Bloom et al. \(2013b\)](#).

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We investigate how technology was transferred in an environment that was extremely conducive to cooperation between firms, the South African goldfields at the turn of the 20th century. Spillovers are by no means guaranteed. For example, Bloom et al. (2013a) find that only 2% of neighboring firms learned any details of improved management practices in an experiment on Indian textile firms. They speculate that textile firm managers were reluctant to pass on information to rival firms who might be tempted to poach key personnel. The lack of vigor-

ous inter-firm competition in South African gold mining make our results (of sharply declining spillovers with distance) even more striking. Mining firms did not have to worry about market competition effects (see e.g., [Bloom et al., 2013b](#)) as firms acted cooperatively for political and economic reasons. The Chamber of Mines opposed increases in taxation and advocated better conditions for European capital from the Transvaal Republic. Most mines jointly hired unskilled labour through the Witwatersrand Native Labour Association and technical knowledge was shared via the Chemical and Metallurgical Society.³ The absence of ‘market stealing’ effects meant that firms in the same mining house, with their different shareholders, may have been unlikely to object to operational knowledge being transferred to other firms. Our results, of co-operative behavior between mines, stands in contrast to the noncooperative behavior found in U.S. oil and gas drilling, see Hendricks and Porter (1996) and [Lin \(2013\)](#).

Our setting is useful as it allows us to distinguish between different methods of technology transfer – physical proximity, organizational affiliation, and key personnel. We observe monthly production data for 116 mines from 1887 to 1907. For each mine we compile data on the tonnes of ore mined, the ounces of gold extracted by traditional and cyanide processes, and key personnel, both operational and administrative. We observe the distance, as the crow flies, between any pair of mines. If physical proximity is critical, then closer mines should experience faster technology transfers than more distant mines. Our study of physical proximity in mining allows us to avoid the problem of agglomeration effects. Gold mines did not locate next to each other to enjoy access to a ‘cheaper and faster supply of intermediate goods and services, proximity to workers or consumers, or a better quality of worker-firm matches (see [Greenstone et al., 2010](#), p. 537). Instead gold mines located where profitable ore was discovered. As each tonne of ore contained only a few ounces of gold, treatment of the ore occurred at the surface above the mine. Therefore, firm distance is effectively exogenous with respect to the level of technology employed by the mine.⁴

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2 Background

2.1 The Witwatersrand Goldfields

In 1886 gold was discovered in the Witwatersrand hills that ran east to west in the south of the Transvaal Republic. As the extent of the gold deposits became clear there was a rapid influx of people to the area. Small-scale diggings of individual miners soon gave way to organized companies. Mining capital mostly came from London with smaller amounts contributed by French and German investors.

The Transvaal Chamber of Mines was formed in October 1887 in the newly settled town of Johannesburg. The Chamber published monthly reports on the operations of its members. It was reformed under various names but continued in its basic mission of advocating the interests of the mine owners and sharing information between mines. A local stock exchange and telegraph also began operations in 1887. Three professional bodies were set up in Johannesburg in the early 1890s. The Association of Mine Managers, the South African Institution of Engineers, and the Chemical, Metallurgical and Mining Society of South Africa all aided the spread of technical and chemical knowledge.⁵

Mining companies were separate legal entities with their own shareholders and boards of directors. Most of the larger mines were floated by one of the nine mining houses (see Table A1 in the Online Appendix). The mining houses held large, not necessarily majority, stakes in the mining companies. The mining houses provided directors for the operating companies, organized loans, and supplied secretarial and engineering expertise. Smaller mines tended to be independently owned and operated.

The earlier mines began to run out of ore and shut down as their reserves were exhausted, starting in the early 1890s. As time passed, the bulk of gold production gradually shifted to the ‘deep level’ mines. By the end of our period, mines reached almost one kilometre below the surface. When the Boer War began in 1899 the mining industry in Johannesburg shut down. Operations were only restarted from mid-1901 onwards. By 1908 mines in the Transvaal, most of which were in the Witwatersrand area, were producing over 7 million ounces of gold per year which amounted around 35% of the world’s production (see 1909 volume of *The Mining Manual*).

⁵See Pogue (2006).

2.2 Metallurgy of Gold and the Cyanide Process

2.2.1 The Mercury Amalgamation Process

In 1886 the conventional method to extract gold from its ore was the mercury amalgamation process. Gold-bearing ores were first crushed and pulverised by massive coal-powered stamp batteries. The crushed ores were then reacted with mercury to form a gold-mercury amalgam. Together with unamalgamated materials the amalgam was sluiced over corrugated copper plates that were covered with mercury.⁶ The amalgam adhered to the copper plates. Finally, the amalgam on the copper plates was heated to a high temperature which made the mercury vaporise, leaving behind the gold.

Particles that failed to form an amalgam, called tailings, also contained a considerable amount of gold, estimated to be around 45% of the initial amount (see [Gray and McLachlan, 1933](#)). The tailings were dumped in giant heaps or dams on the Rand because knowledge of an appropriate treatment was lacking in the 1880s (see [Eissler, 1888](#)).

Mercury amalgamation was less effective for ore buried at deep levels since deep-level ore was unoxidised and contained a large amount of pyrites (iron sulphides). Gold output from the use of mercury decreased as mines delved deeper and deeper. Various attempts were made to overcome this issue. For example, unoxidised ore was ground more finely, or the ground ore was passed through a chlorine solution ([Lougheed, 1989](#)). Although chlorination was chemically effective it was quite expensive and therefore not used by mines with lower quality ore.

2.2.2 The Cyanide Process

The solubility of gold in a cyanide solution has been known since the Middle Ages. However, cyanide was not a profitable extraction method when it was first discovered (see [Eissler \(1898\)](#)). In the cyanide process, gold (Au) and the cyanide anion (CN-) in potassium cyanide (KCN) form a soluble compound: potassium dicyanoaurate ($\text{KAu}(\text{CN})_2$). The potassium dicyanoaurate solution is easily separated from other substances through filter vats and is then placed in a precipitation box containing zinc. Gold detaches from potassium dicyanoaurate in the precipitation box and falls to the bottom.

The cyanide process was developed in Scotland by John MacArthur and the Forrest brothers. The process was patented in the U.K. in 1887 and in the Transvaal Republic in September 1888. The cyanide process treated tailings after mercury amalgamation. Ores were treated by mercury amalgamation before they were sent for cyanide treatment. Some mines concentrated tailings before cyanide treatment. Concentrates, which had a very high percentage of gold, were treated

⁶Some mines used mercury in the stamp batteries whereas others added mercury to the copper plates.

separately with cyanide. The remaining material was divided into sands or slimes based on the size of the particles. Sands were coarser particles and slimes were finer particles. The cyanide process was first used to treat sands. It was only in 1897 that a treatment for slimes was pioneered (see [Eissler, 1898](#)).

The first commercial application of the cyanide process took place on the Witwatersrand goldfields. The first cyanide plant was built at the Salisbury mine for demonstration purposes in 1890. In 1891 the Robinson mine first used cyanide for operational purposes.⁷

Royalties had to be paid to use the MacArthur-Forrest process until November 1896, when the patent was found to be invalid by the High Court of the Transvaal Republic ([Gray and McLachlan, 1933](#)). Mining companies had sued the patent holder, the African Gold Recovery Company, alleging that knowledge of treating gold ore with cyanide had been known well before the MacArthur-Forrest patent was granted.

Opinions on the novelty of the cyanide technique varied. The *South African Mining Journal* opined on December 23, 1893 that, “there can be no question that the MacArthur-Forrest process has been of the utmost service to the Witwatersrand mining industry”. The *Engineering and Mining Journal* wrote in September 1894 that the MacArthur-Forrest process was successful due to the innovative use of zinc shavings to precipitate the gold following treatment with cyanide. Mining companies were forced to pay an average of 7.5 per cent of the gold extracted to the African Gold Recovery Company (see [Gray and McLachlan, 1933](#)).

The adoption of cyanide on the Rand increased gold production by roughly 50 per cent in the first month of its use. However, it would be wrong to view cyanide as a single innovation. After the first use of cyanide there was continued development of ‘microinventions’ (see [Mokyr, 1990](#)). [Mann \(1909\)](#) notes improvements such as adding halogen salts (1892), agitation and filter pressing (1893), electric precipitation (1894), roasting of sulphate-telluride ores (1895), the addition of soluble lead (1896), tube milling (1898), vacuum filters (1903), and automatic suction filters (1905). In addition, the benefit of using oxygen in the cyanide process was not discovered by practitioners for years after the MacArthur-Forrest patent was granted. The strength of the potassium cyanide solution also had to be optimized. The initial strength ranged from 0.25 to 1.0 per cent, sometimes as high as 2.0 percent. After experimentation it was found that a more dilute cyanide solution, of around 0.2 per cent, extracted the most gold ([Gray and McLachlan, 1933](#)).

The constantly improving cyanide technology facilitated the expansion of the gold mining

⁷A number of firms were formed to process mines’ ore with cyanide at the mine site. The African Gold Recovery Company, the Transvaal Chemical Company, Rand Central Ore Reduction Company, and the Robinson Custom Works were the most prominent.

industry in South Africa. The cyanide process remains a mainstay of the global gold mining sector (see Verbrugge et al., 2021). The slow but continual productivity improvements we demonstrate in mining have also been documented in the mechanization of the French textile industry during the 19th century see Juhász et al. (2021).

3 Data and Measurement

3.1 Data

We hand collect mine-level production data for all mines in the Transvaal over the period 1887-1907 from various sources.⁸ The Chamber of Mines published annual reports, which include monthly production data for each active mine in the Transvaal. We augment our data with *The Mining Manual* and *The Economist*. We observe the monthly tons of ore processed by mercury amalgamation (the primary, or non-cyanide, process) and the ounces of gold extracted. We also observe the monthly tons of sands, slimes, and concentrates processed (with the secondary, or cyanide, process) and the ounces of gold extracted by each process.

The locations of mines come from maps of the goldfields that depict each mine’s surface area. We identify the approximate centroid of each mine and use the coordinates of the centroid as the mine’s location. Most mines are located on the Witwatersrand, which runs for roughly 60-kilometres east to west near Johannesburg. We collect company data from *The Mining Manual*. This periodical reports the details of all companies in our sample. We collect the names of directors, company secretaries, managers, and mining engineers whenever available. We supplement *The Mining Manual* with company reports published in *The Financial Times*. We collect a mine’s affiliation with a mining house from public reports, such as by the Witwatersrand Native Labour Association, companies’ annual reports, and newspaper commentary.

We drop mine-month observations with missing production data. For each mine, the first and last observations in each consecutive production period are also dropped because production in these months often includes irregular activities (such as trial milling, setting up plates, and final clean-ups) that lead to extreme values. Production data are unavailable from November 1899 to April 1901 as mining activity was interrupted by the Second Boer War. Mines started resuming work in May 1901, yet production activity did not regain the pre-war level until the end of 1901. For each extraction process in a mine-month, we drop the observation unless both the ounces and tonnage of that process were reported. Last, we require mines to have reported at least 12 months of production activity after the above restrictions. The final sample contains

⁸The region we study was politically part of the Transvaal Republic in 1887. Following the Second Boer War it became the Transvaal colony in 1902 before joining the Union of South Africa in 1910.

9659 mine-month observations, of which 7589 observations have both primary and secondary process data.

3.2 Cyanide Productivity

Our outcome variable, cyanide productivity ($Productivity^{Cyanide}$), measures the percentage of gold in the ore that can be extracted through cyanidation. In our baseline analysis, we focus on the largest cyanide process, the treatment of sands. We examine the productivity of slimes and concentrates in the robustness section. Since the amount of gold in its ore is not observable, we make three simplifying assumptions: (1) the percentage of gold in its ore that is recovered by mercury amalgamation is constant, (2) the proportion of ore lost after the amalgamation process, but before the cyanide process, is constant, and (3) a constant proportion of gold is sorted into sands.

If these three assumptions hold, true (but unobservable) cyanide productivity is proportional to the ounces of gold extracted via cyanidation divided by the ounces of gold extracted by mercury amalgamation (see Online Appendix for details.):

$$Productivity_{i,t}^{Cyanide} \propto \frac{Ozs_{i,t}^{Cyanide}}{Ozs_{i,t}^{Primary}}. \quad (1)$$

Intuitively, our measure of cyanide productivity controls for the (unobserved) amount of gold present in the ore. We use the amount of gold extracted via mercury amalgamation as a proxy for the amount of gold in the ore. Although we also use mine fixed effects, these will not be fully adequate, since the amount of gold per unit of ore tended to decline as mines became deeper. Thus, we also control for mine depth in the regression analysis.

We believe our assumptions are plausible. Mercury amalgamation was an established technology that has been around since the Middle Ages. Advances in mercury amalgamation technology are unlikely to have taken place, or are at least of second order relative to improvements in cyanide technology. However, one might worry that the chemical composition of ores might affect the recovery rate from mercury amalgamation. Since 97% of our observations are located in a 60-kilometre range, the chemical property of ores should be similar. To further alleviate this concern, we estimate spillover effects conditioning on mine fixed effects and the cumulative extraction tonnage and its squared term. Cumulative extraction acts as a proxy for mine depth.

As for the second assumption, tailings were usually sent directly to the cyanide plant after amalgamation. The amount of ore lost between the two processes was limited. The amount of ore washed or blown away was probably small, and as long as the amount lost was random, it will not cause bias in the estimation.

We examine the importance of our third assumption empirically. Our results are consistent if we relax the last assumption by aggregating the sands, slimes, and concentrates processes to measure cyanide productivity. This alternative (total) cyanide productivity is: $Productivity^{Cyanide} = \frac{Ozs^{Sands+Slimes+Conc}}{Ozs^{in\ tailings*}} \propto \frac{Ozs^{Sands+Slimes+Conc}}{Ozs^{Primary}}$.⁹ The alternative measure does not require assumption (3). We use this alternative measure in the robustness section and the results are consistent with the baseline analysis.

A final concern is that mines would sometimes store tailings in a heap or a dam for later cyanide treatment rather than processing them immediately. Such behavior would lead to a timing issue in the cyanide productivity measure: tailings treated at time t are not mined at time t but could also be from earlier periods. Therefore, time t 's mercury extraction productivity may be an inappropriate control for time t 's cyanide productivity. To alleviate this concern, we review all remarks in the Chamber of Mine's annual reports and remove the tonnage and ounces reported as coming from accumulated tailings from the original data whenever possible. Figure B1 in the Online Appendix indicates that the tonnage treated by cyanide was approximately equal to the tonnage treated by mercury amalgamation. Losses due to ore being washed or blown away appear to be small.

3.3 Cyanide Knowledge Pool

Our key explanatory variable, $KnowledgePool(m)_{i,t}$, is an approximation of the cyanide knowledge that can be learned by focal mine i at time t through mechanism m . Individual mines' cyanide knowledge is not directly observable. A mine's cyanide productivity per se is not a suitable proxy for cyanide knowledge because productivity may be sensitive to mine location, ore quality, or other factors. Instead, we consider the deviation of actual productivity from a regression based measure of expected cyanide productivity. This difference indicates a mine's above- or below-average ability to use the cyanide method. We estimate cyanide productivity with the following regression:

$$Productivity_{j,t}^{Cyanide} = \alpha_j + \gamma \mathcal{X}_{j,t} + \delta_t + \epsilon_{j,t}$$

where α_j is a mine fixed effect that controls for ore quality due to time-invariant mine characteristics like location.¹⁰ $\mathcal{X}_{j,t}$ is a vector of control variables, including the cumulative

⁹*tailings** denotes the true, but unobserved, ounces of gold in tailings.

¹⁰We include all available observations to estimate the cyanide method production function in the baseline analysis. This approach is similar to the regression-based estimation of total factor productivity (see, for example Imrohoroglu and Tüzel (2014); Olley and Pakes (1996)). Despite the generality of this approach, using full-sample information is likely to incur issues of reverse causality. Therefore, we also predict the out-of-sample cyanide productivity at time t based on a model only using information available at $t-1$. In the out-of-sample prediction, we assume the time fixed effects are the same in t and $t-1$. The results based on the rolling estimation are

extraction and its squared term, indicators for irregular mining activities like the concentrates process, the slimes process, mine stoppages, cleanups, by-products, business connections, and use of the tailings dump. δ_t is a time fixed effect that captures productivity shocks common to all mines at time t . The unexplained residual, $\epsilon_{j,t}$, is the mine-specific above/below average cyanide productivity which we use as our measure of cyanide knowledge.¹¹ We assume that only productivity above the expected level contains information that can induce learning, following [Conley and Udry \(2010\)](#). Therefore an individual mine’s cyanide knowledge, $K_{j,t}$, is the positive residual productivity: $\max\{0, \epsilon_{j,t}\}$.¹²

From individual mines’ cyanide knowledge, we use a connection intensity-weighted average across all connected mines as the Knowledge Pool measure available to mine i at time t :

$$Knowledge\ Pool_{i,t}^m = \sum_{c_{ijt}^m=1} g_{ijt}^m \times K_{j,t}$$

where c_{ijt}^m is a binary variable equal to 1 if mine i and j are connected through mechanism m at time t and g_{ijt}^m is a variable that ranges from 0 to 1 that indicates the connection intensity.¹³

We construct five knowledge pools corresponding to the five potential spillover mechanisms under examination: organizational, personnel, geographical, French, and German connections.

3.3.1 Organizational Knowledge Pool

We use mining house affiliation to study the role of organizations in the diffusion of cyanide knowledge. The connection dummy, c_{ij} , equals one if two mines were members of the same mining house.¹⁴ We assume that each mine is equally likely to learn from all other affiliated mines; thus, the connection intensity is the same for all connected mine-pairs: $g_{ij}^{Org} = 1$. The organizational knowledge pool is a summation of the cyanide knowledge of other mines in the same mining house:

quantitatively similar to the baseline result.

¹¹Our approach is similar to [Jenter and Kanaan \(2015\)](#) who adopt an industry index model to decompose a firm’s stock return into a systematic component and a firm-specific component, with the firm-specific component capturing, among other things, CEO ability. In our setting, we consider the residual productivity captures a mine’s ability to apply the cyanide method. Clearly, the residual may also represent model misspecification and/or white noise. Estimation results are reported in Table A2 in the online Appendix.

¹²By setting the negative residuals to zero, we assume that mines do not learn from other mines that experienced worse than expected performance. Effectively we assume that mine’s share their successful techniques with others but not their unsuccessful techniques. We relax this assumption by adopting two alternative transformations of the residual productivity: (1) exponential transformation: $K_{j,t} = \exp(\epsilon_{j,t})$, and (2) parallel shift: $K_{j,t} = \epsilon_{j,t} + \min(\epsilon_{j,t})$. The results based on these alternative transformations are quantitatively similar to the baseline results.

¹³An unweighted knowledge pool is used in the robustness section, where $g_{ijt}^m = 1$ for all mechanisms.

¹⁴There are no instances of mines changing their mining house.

$$Knowledge\ Pool_{i,t}^{Org} = \sum_{i \neq j, c_{ij}^{Org}=1} K_{j,t}$$

For an independent mine i that was not affiliated to a mining house, the connection dummy c_{ij}^{Org} equals zero for all j and therefore $Knowledge\ Pool_{i,t}^{Org}$ also equals zero.

3.3.2 Personnel Knowledge Pool

We study mine personnel interlocks to examine the role of individual networks in the diffusion of the cyanide technology. We examine the role of operational personnel (engineers and mine managers) in the baseline analysis and explore the role of white-collar personnel (company directors and secretaries) in the robustness section. We follow [Zacchia \(2020\)](#) to construct the knowledge pool measure through contemporary connected personnel.¹⁵ Mine i and j are connected through a manager interlock at time t if they had any common managers at time t . The connection intensity is an increasing function of the proportion of overlapping managers in two mines: $g_{ijt}^{Manager} = f(\frac{2 \times \#CommonManager}{\#Manager_{it} + \#Manager_{jt}})$. The knowledge pool through manager interlocks is a weighted sum of cyanide knowledge of interlocked mines:

$$Knowledge\ Pool_{i,t}^{Manager} = \sum_{i \neq j} f(\frac{2 \times \#CommonManager}{\#Manager_{it} + \#Manager_{jt}}) \times K_{j,t}$$

where $f : [0, 1] \rightarrow [0, 1]$, $f(0) = 0$ and $f(1) = 1$ following [Zacchia \(2020\)](#). We apply the square-root function to the proportion of common manager in the baseline result.¹⁶ In addition to common managers in the contemporary year, we also consider connections through a manager's past work experience. A historical connection between mines i and j exists if i 's manager worked at mine j in the previous three years but not in the current year. Similarly, in the robustness section we construct two additional measures, $Knowledge\ Pool_{i,t}^{Director}$ and $Knowledge\ Pool_{i,t}^{Secretary}$, to investigate whether white-collar personnel facilitate knowledge transfer.

3.3.3 Geographical Knowledge Pool

The geographical knowledge pools depend on the physical distance between mines. The connection dummy c_{ijt}^{Geo} equals 1 if the distance between two mines d_{ijt} was no greater than D

¹⁵In [Zacchia \(2020\)](#) a connection exists between two inventors if they have collaborated on past patents. We use personnel who were common to multiple mines.

¹⁶We show in the robustness section that the empirical results are quantitatively similar base on alternative choices of function f , including (1) linear transformation: $f(x) = x$, (2) polynomial transformation: $f(x) = -x^2 + 2x$, and (3) square transformation: $f(x) = x^2$.

kilometres. We assume that a mine is more likely to learn from closer mines than more distant mines. We define the connection intensity as a monotonic function of the inverse distance between two mines: $g_{ijt}^{Geo} = f(1/(1 + d_{ijt}))$. Therefore, the geographical knowledge pool equals:

$$Knowledge\ Pool_{i,t}^{Geo} = \sum_{i \neq j, d_{ijt} \leq Dkm} f\left(\frac{1}{1 + d_{ijt}}\right) \times K_{j,t}$$

Similarly to the personnel knowledge pool we apply the square-root function to the connection intensity in the baseline analysis and show that the results are robust to alternative functional forms.

3.3.4 French and German Knowledge Pool

We define a mine as having a French and/or German connection if there was an office for that mine anywhere in France and/or Germany. Two mines are connected if they both had French(German) offices at time t . The connection intensity equals one for all connected mines. Therefore, the knowledge pool through French(German) connections is an unweighted sum of cyanide knowledge of all other mines that also have French(German) offices:

$$Knowledge\ Pool_{i,t}^{French(German)} = \sum_{i \neq j} French(German)\ Office \times K_{j,t}.$$

For mines with no French and / or German connection, $Knowledge\ Pool_{i,t}^{French}$ and/or $Knowledge\ Pool_{i,t}^{German}$ equals zero.

4 Results

4.1 Summary Statistics

In [Table 1](#), we present summary statistics for the 116 mines in our sample. An average mine processed 9.6 thousand tons of ore using the primary (mercury) amalgamation method and 8.1 thousand tons of sands using the cyanide process per month. The gold recovery rate, defined as the ounces of gold per ton of ore treated, averaged 0.41 for the primary process and 0.15 for the sands process. 77% of our mine-months involved the use of cyanide to treat sands, 33% used cyanide to treat slimes, and only 20% used cyanide to treat concentrates.

[Insert Table 1 Here]

The average mine had a cumulative extraction of 0.48 million tonnes of ore. 9% of mines had had a business connection with an external cyanide processor in the previous year.¹⁷ Most

¹⁷Such as the African Gold Recovery Company, the Transvaal Chemical Company etc.

mines were members of one of the nine mining houses, the remaining 32% were independent mines. **Figure 1** depicts mine locations by mining house on a modern-day map. 96% of all mines were in the Witwatersrand region of the Transvaal. The map shows that despite some location clustering, geographical variation exists for most mining houses.

[Insert Figure 1 Here]

The mean mine had almost 8 directors, 1.68 managers or engineers, 1.81 secretaries, and 2.16 management boards. Most mines had two official boards of directors, one in London and the other in South Africa. Some also had a French or German 'committee' to represent their shareholders' interests. 41% of all mine-months had a French connection (i.e., an office in Paris). This connection could be an individual at an office address, a bank, or sometimes a representative company, with locations scattered around Paris. It was rare for there to be a formal French committee. No French or German offices were reported before 1895. The proportion of mines with a French office grew rapidly in later years. 9% of mine-months had a German connection. In contrast to French connections, all German-connected firms used the same agent, "Deutsche Treuhand Gesellschaft" (German Trust Company), and had a formal committee of three members for all mines that they represented.

Table A3 in the Online Appendix reports the proportion of connected mine-pairs over time: about 7% of mine-pairs were connected through a common mining house, 10% were connected through geographical proximity if we set $D = 2.5km$. These two networks were relatively stable over time. Mines with manager interlocks were less than 1% of the sample in the early 1890s, but this number gradually grew to 7% by 1907.

Figure 2 is a visual representation of active mines over time. Mines might temporarily shut down for several months or completely shut down for good. The number of active mines and cyanide-using mines each year is plotted in **Figure 3**. Approximately 60 mines were active each year, excluding the Boer War period. The number of cyanide-using mines increased rapidly after the introduction of the cyanide process in 1890. After 1895, there were very few mines not using cyanide.

[Insert Figure 2 and Figure 3 Here]

In **Figure 4** we show how the cyanide process contributed to total gold output over time with output data aggregated at the annual level. Mines using cyanide increased their gold output by approximately 50%, primarily due to gold recovered from sands. The proportion of gold produced by the cyanide process increased gradually during our sample period. We also

observe an increase in the proportion of gold recovered from slimes, after the slimes technique debuted in 1898.

[Insert Figure 4 Here]

4.2 The Adoption of the Cyanide Process

We first examine how technology diffuses at the extensive margin. We model mines' decisions to adopt the sands process in the early 1890s and the slimes process in the late 1890s. Tailings were sorted into sands and slimes, and the first use of cyanide was to treat sands. A micro-invention was developed around 1897, making the cyanide treatment of slimes feasible. We model the adoption of the sands and slimes processes, given a mine's knowledge of cyanide from its neighbors, using both ordinary least squares (OLS) and a hazard model. The knowledge pools depend upon neighboring mines' use, or not, of the sands and slimes cyanide processes.

[Insert Table 2 Here]

In [Table 2](#) we show the technology spillover effects of the adoption of the sands and slimes processes. The adoption decisions were affected by the number of other mines in the same mining house that had adopted that process. We find that one extra cyanide-using mine in the same mining house increased the probability of sands cyanide adoption by 2 percentage points per month (column 1), and this positive association is confirmed by the hazard model (column 2). Mining houses were the instigators of cyanide adoption, physical proximity was irrelevant. Managerial/engineering connections were not important for the adoption of cyanide, but in the pre-1895 period less than one percent of mines had common operational personnel (see [Table A3](#) in the Online Appendix).¹⁸

For the slimes process adoption we find that the adoption decisions were positively affected by the slimes cyanide usage of mines with the same manager. We find that one extra slimes cyanide-using mine with a common manager increased the probability of slimes adoption by 5.4 percentage points per month (column 3), and the hazard model finds qualitatively similar results. Although mining house affiliation alone does not matter, mine managers and engineers could be assigned to multiple mines within the mining house to facilitate technology transfer. In the early 1890s, manager interlocks were less common than in the late 1890s. We also find evidence that knowledge of the slimes process was propagated through German connections but not French connections. One extra German-connected mine that used slimes cyanide increased

¹⁸We ignore French and German connections for the sands process adoption as very few mines had those connections before 1895.

the probability that a German mine would adopt the slimes process by 3.8 percentage points per month (column 3), and the hazard model also suggests significant technology spillovers among German-connected mines (column 4).

4.3 Cyanide Process and Productivity Gain

We now examine the impact of the cyanide process on the gold recovery rate. [Figure 5](#) shows that the total recovery rate (the mercury amalgamation recovery rate plus the cyanide recovery rate) increased substantially immediately after using cyanide. In contrast, the primary recovery rate remained relatively stable after the use of cyanide. This suggests the gold output from cyanide is an additional output, rather than gold output being substituted from mercury to the cyanide method.

[Insert Figure 5 and Table 3 Here]

[Table 3](#) regresses the gold recovery rate on an indicator variable that indicates whether the mine has adopted cyanide. Columns (1) to (3) show that an additional 0.26-0.28 ounces of gold were recovered from each ton of ore treated by cyanide. This increase is more than 50% of the median total recovery rate one year prior to the adoption (median = 0.52 and mean = 0.61 in the [-12, -1] adoption window). However, selection issues may be important. The increase in the total recovery rate could be driven by a mine’s decision to adopt cyanide when it reached high quality ore veins. Therefore, we test whether the primary recovery rate was affected by the adoption of cyanide. Columns (4) to (6) show no significant difference in the primary recovery rate after the adoption of the cyanide process. Therefore, the productivity gain was mainly obtained from cyanidation and selection effects appear slight.

4.4 The Diffusion of Cyanide knowledge

[Table 4](#) presents our main results on cyanide knowledge spillovers. We test whether an increase in other mines’ cyanide productivity affected a mine’s productivity through the regression:

$$Productivity_{i,t}^{Cyanide} = \sum_{m \in \mathcal{M}} \beta_m Knowledge Pool_{i,t-1}^m + \gamma \mathcal{X}_{i,t} + \alpha_i + \delta_t + v_{it} \quad (2)$$

where $\mathcal{M}$ is the set of the five mechanisms of interest and $\mathcal{X}_{i,t}$ is a vector of control variables, including the (quadratic form of the) cumulative extraction of ore that captures the variation in ore quality due to mine depth. We also condition on lagged own cyanide knowledge, the use of by-products, slimes process, and concentrates processes, business connections, mine stoppages, mine clean-ups, the use of cyanide on accumulated tailings, and French/German connections.

We use mine fixed effects α_i to capture differences in (unobservable) ore type driven by mine location.¹⁹ Month-year fixed effect δ_t are used to control for common productivity shocks in each month, such as floods, droughts, and labor shortages.

[Insert Table 4 Here]

Columns (1) to (5) test the five mechanisms separately. We find strong knowledge spillovers through organizations (mining houses), manager interlocks, geographical proximity (when the distance parameter D is set to 2.5 kilometres), and a shared German connection. We discover little evidence that French connections facilitated knowledge transfer. The different results for French and German connections are likely due to French connections being weaker than German ones. All German connections indicate a shared office in Berlin with a dedicated committee to represent German shareholders. In contrast, French connections were more tenuous, there were many agents and offices for South African mines in Paris. These French agents may not have been in frequent contact with each other.

In the single knowledge pool regressions the coefficients for a particular knowledge pool may be confounded by other knowledge pools. For example, some mines with a common manager are located near each other. Therefore, the manager knowledge pool may also partly capture geographical spillovers if they exist. In column (6) we include all five spillover measures and test their joint significance. After controlling for other confounding knowledge spillover mechanisms, the coefficient of the organizational knowledge pool becomes indistinguishable from zero. However, all other mechanisms remain statistically significant and of a similar magnitude. This finding does not suggest that mining houses played no role in facilitating knowledge spillovers. Instead, mining houses enabled the diffusion of new practices and procedures among affiliated mines by appointing a common manager, or consulting engineer, to oversee multiple mines. The joint significance test of the coefficients on these five knowledge pool variables has an F statistic of 8.79; hence, at least one of these knowledge pools is essential for knowledge transfer.

We now quantify the economic magnitude of these estimated coefficients. In column (6), all else equal, a one standard deviation increase in the external managerial/geographical/German knowledge pool is associated with an 0.011/0.013/0.008 increase in cyanide productivity. If we consider the estimate of 0.013 productivity spillover for a median mine in the cyanide-using sample, it is equivalent to a 3% increase in the cyanide productivity (median = 0.43, mean = 0.48) and a 0.9% increase in the total gold recovery rate. These figures relate to approximately an extra 36 ounces of gold that could be recovered per month. The spillover value of this

¹⁹Differences could be the amount of gold in the ore or the chemical composition of the ore. Some ore types were more amenable to cyanide usage than others.

incremental monthly output is nearly \$70,000.²⁰

4.4.1 The role of personnel and common ownership

We examine how spillovers depend upon a mine’s personnel in Table 5. We separate personnel into white-collar (directors and secretaries) and blue-collar (mine managers and engineers). Technical knowledge might have been shared between mines by white-collar workers at board meetings or via written reports. In Table 5 we find that neither current director interlocks nor a common secretary were effective in facilitating technology transfer. Mine managers and engineers were involved in the daily mining operations, and this hands-on experience appears to have been necessary to transfer cyanide expertise.

[Insert Table 5 Here]

Our work also touches on the role of common ownership and innovation (see Vives 2020; Anton et al 2021; Schmalz 2018). Mines within the same mining house had high levels of common ownership, with the mining house itself providing much of the equity capital. Once we condition on geography, operational personnel, and French/German connections, we find no effect of common ownership (i.e., Knowledge Pool (Org)) on knowledge spillovers (see Table 5, column 4). Company directors are also ineffective in disseminating knowledge between mines.

4.5 Robustness to Alternative Explanations

4.5.1 Market Rivalry Effect

One issue in identifying knowledge spillovers is the potential confounding of technology spillovers with market rivalry effects (Arora et al., 2021; Bloom et al., 2013b). This issue is less of a concern in our setting because most of the world, and Great Britain in particular, was on the gold standard (Eichengreen and Flandreau, 1985). The Bank of England had been required by law, since 1821, to exchange a fixed quantity of gold for bank notes. Hence, any increase in total gold output, via knowledge spillovers for example, could not adversely affect the market price or the quantity of gold demanded.

4.5.2 Endogenous Manager Assignment

A concern about our interpretation of managerial spillovers is that a common manager might be appointed to two or more mines when those mines have unusually high, or low, cyanide productivity. Such a selection effect might wrongly appear to be a technology spillover. To

²⁰This amount is calculated using the gold price on 17/03/2022 at 2022 dollar value.

partially address this concern we examine historical managerial interlocks based on our personnel data. A historical interlock exists if a mine manager/engineer worked at another mine in the previous three years but not in the current year. If selection effects are present then historical manager interlocks may still be associated with our measure of spillovers. However, if personnel are useful for transferring state-of-the-art knowledge of cyanide usage, then historical connections are unlikely to be useful. [Table 5](#) shows that historical managerial interlocks have statistically insignificant and near zero effects on spillovers. This test shows no evidence of selection effects.

4.5.3 Spatially Correlated Productivity Shocks

We face limited concerns about reverse causality since we test how a reference group’s past productivity affects the current productivity of a mine. Moreover, we control for lagged own above expectations productivity. Our specification partially addresses concerns about unobservable factors that might drive simultaneous productivity shocks across mines, such as a mining area hitting richer or poorer veins of ore. However, one might still worry that the observed positive correlation between productivity and neighbouring mines’ lagged productivity surprises could be driven by both spatially and serially correlated unobservable productivity shocks, such as water shortages or floods. We cannot rule out this possibility. Nonetheless, we turn to a battery of robustness checks to demonstrate that spatially correlated unobservable factors do not solely drive the positive correlation of productivity shocks between neighbouring mines.

[Insert Table 6 Here]

In [Table 6](#), we compare geographical knowledge spillovers between cyanide technology leaders and laggards. We expect that mines already at the technology frontier have less to learn from their neighbours whereas laggard mines have more room to improve. If the positive coefficient on geographical knowledge pool only captures spatially correlated shocks, the coefficient should be similar for technology leaders and laggards. Thus, we run a split sample test based on cyanide productivity and cyanide experience. Column (1) presents the results for above median cyanide productivity mines. The coefficient estimate for the geographical knowledge pool is 0.001 and statistically insignificant. In column (2), the estimate for the same coefficient for the bottom 50% cyanide productivity mines is 0.018, which is both economically and statistically significant. Columns (3) and (4) suggest that a one standard deviation increase in the geographical knowledge pool is associated with an increase in cyanide productivity of 0.007 for technology early adopters and 0.014 for later adopters. In unreported results, we include interaction terms between the bottom/novice mine dummy with all control variables to test whether

the difference in knowledge spillover effects between top and bottom (veteran and novice) mines is statistically significant. We find bottom cyanide productivity mines benefit significantly more from their geographical neighbours' cyanide knowledge than top cyanide productivity mines. Overall, we conclude that less experienced mines enjoyed faster productivity growth through learning than technological leaders. This result suggests that spatially correlated shocks are unlikely to be the main explanation for our results.

4.5.4 Placebo Tests

We run several placebo tests to further rule out the possibility that our findings are caused by unobservables. First, we run a placebo test using the primary (mercury amalgamation) process. The use of mercury amalgamation to recover gold can be traced back to the 4th century BC, and it was the standard gold extraction process at the start of mining operations on the Witwatersrand. Thus, we consider mercury amalgamation to be an established technology for gold mines. The literature suggests that knowledge spillovers only exist when there is something new to learn (Conley and Udry, 2010; Foster and Rosenzweig, 1995; Foster and Rosenzweig, 2010; Juhász et al., 2021). Therefore a mine's peers should not generate knowledge spillovers for the mercury amalgamation process, since there was little new to learn.

[Insert Table 7 Here]

?? shows that only the geographical knowledge pool is statistically significant in explaining spillovers of mercury knowledge when the five mechanisms are tested separately. In column (6) all coefficient estimates of knowledge pools are separately insignificant at conventional levels. Furthermore, a joint significance test fails to reject the null hypothesis that all coefficients on the five knowledge pools are equal to zero ($F = 1.02$). The limited evidence of mercury amalgamation knowledge transfers suggests the positive and significant cyanide spillovers observed in our baseline results do not just reflect a correlation of productivity shocks among connected mines.

[Insert Figure 6 Here]

We now conduct 1000 Monte Carlo simulations of mine connections. In each simulation, a connection dummy is randomly assigned to all possible mine pairs so that 10% of mine pairs are connected. A random connection intensity is then assigned to the connected mine pairs. The connection and connection intensity are bilateral and constant over time. We construct a pseudo-knowledge pool based on this randomly generated network analogous to $knowledge\ pool(m)$ and

estimate its coefficient using the baseline model. **Figure 6** presents the fitted kernel density of the coefficient estimates of the randomized knowledge pool which is centered on zero. Two vertical lines, indicating the estimated manager spillovers and geographical spillovers, are to the far right of the fitted density curve. No simulation has an estimated coefficient higher than 0.01, which suggests the probability of a false-positive is near zero.

4.6 Robustness Results

4.6.1 Model Specification

In **Table 7** we examine the assumptions we have made about: the timing of the knowledge transfer; the definition of the cyanide process; the measure of cyanide productivity; the construction of the cyanide knowledge pool; and the model specification. We vary one assumption at a time and test whether the results are consistent with our baseline results.

[Insert Table 8 Here]

In panel A we relax the assumption regarding the timing of spillovers. Our baseline results use a lagged one-month positive productivity surprise. We now test whether mines could learn from cyanide innovations that took place several months ago. The cyanide knowledge pools in columns (1) to (3) are based on the average 3, 6, and 12 month lagged above expectation productivity. The *Lagged own knowledge* control variable is defined using the average own above expectation productivity over the same period. Geographical knowledge spillovers diminish in magnitude when the cyanide innovation is from a more distant period, but the magnitudes of manager spillovers are similar in all three columns. One explanation is that close geographical proximity speeds up knowledge transfer. Employees of geographically close mines are likely to interact, so news about cyanide technology might be easily transmitted within a short time. Workers or managers in commonly managed mines, on the other hand, may visit the mining house headquarters (in downtown Johannesburg) less frequently and information exchange may be delayed.

In panel B, we examine knowledge spillovers of all the cyanide processes, not just the sands process. Our results suggest that including the slimes, concentrates, or both knowledge pools do not change our conclusion. The results in column (3) also confirm that our assumption that a constant proportion of gold in tailings is sorted into sands does not affect the results, since all tailings are included in column (3).

In panel C, we test the robustness to three alternative measures for cyanide productivity: (1) gold ounces from sands per ton of sands tailings treated, (2) gold ounces from sands per

ton of crushed ore treated, and (3) gold ounces from sands per ton of sands treated scaled by the gold yield from amalgamation per ton of crushed ore treated. Compared to the baseline measure, the measures in columns (1) and (2) do not adjust for the underlying ore quality. However, all results include mine fixed effects which mitigates the lack of a direct control for ore quality. The measure in column (3) addresses the concern that not all ore crushed in month t may have been treated as tailings in that month. This metric assumes that the proportion of gold sorted into sands from tailings is proportional to the ratio between the tonnage of sands and crushed ores (i.e. $\frac{Ozs^{in\ sands}}{Ozs^{in\ tailings}} \propto \frac{Tons^{Sands}}{Tons^{Primary}}$). However, partially treated sands tailings could contain more gold than untreated sands. Moreover, the ratio could be sensitive to the moisture level of the sands and crushed ores. The results based on these alternative measures are qualitatively similar to the baseline results.

In panel D column (1), we test a sub-sample that consists of mines registered before 1890 to address the concern that mine locations might be endogenously determined by cyanide knowledge spillover potential. In this sub-sample, mine locations were determined and registered before the cyanide method was used on the Witwatersrand in 1890. Thus, these mines' locations are unlikely to have been affected by characteristics that affect cyanide productivity, which alleviates the endogenous location choice concern. The coefficient estimate of the geographical spillovers is 0.013 with a standard error of 0.04, consistent with the baseline result. The manager spillover and German connection spillover are still positive but less statistically significant in this sub-sample. As about 40% of our sample mines were registered after 1890, the sample restriction may lead to a loss of information that would be useful to identify the manager and German spillovers. In column (2), we predict the expected cyanide productivity using a rolling estimation window with all observations up until month $t - 1$, rather than using full sample data as we do in our baseline results. Our results are robust to the knowledge pool constructed based on the dynamic estimation of the expected cyanide productivity. Column (3) modifies the knowledge pool to address the concern that an increase in the knowledge pool could be due to an increase in the number of connections instead of an increase in 'true' cyanide knowledge. Hence, we construct a 'max' knowledge pool with only the highest productivity surprise of a connected mine. This knowledge pool measure is less sensitive to market entry/exit and the size of the connections network. We find quantitatively similar results relative to the baseline specification. Last, in column (4), we assume mines have a Cobb-Douglas production function with the external knowledge pool as an additional factor of production. The Cobb-Douglas functional form implies the relationship between productivity and the knowledge pool should be estimated in a log-log regression form. The log-log model finds coefficient estimates on the

manager knowledge pool and geographical knowledge pool to be 0.007 and 0.008, respectively, suggesting a 1% increase in a neighbouring mine's lagged productivity is associated with a 0.007% increase in productivity.

Last, in Panel E, we apply alternative weights for connected mines' cyanide knowledge. Column (1) examines the assumption regarding manager interlock intensity and geographical connection intensity by forcing all connection intensities to equal one. Columns (2) to (4) present the results based on alternative transformations of the connection intensity measure following [Zacchia \(2020\)](#), including linear, square, and polynomial transformations. All three transformations provide results consistent with the baseline analysis, suggesting that our results are not sensitive to the choice of the transformation function of the connection intensity.

4.6.2 Geographical Spillovers

Geographical knowledge spillovers are based on the idea that people are more likely to exchange information when they are located nearby and the knowledge spillover effect should diminish with the geographic distance.²¹ We now explore the sensitivity of spillovers to distance. ?? presents the spillover effects from neighbouring mines: (1) within a 2.5 kilometres radius from each other, (2) mines outside a 2.5 km radius but within a 5 km radius, and (3) mines outside a 5 km radius but within a 10 km radius. Geographical spillovers are extremely localized. There is no statistical evidence for knowledge spillovers from mines located more than 2.5 km away, and the point estimates for more distant mines are virtually zero.

[Insert Table 9 Here]

4.6.3 Multiple Spillover Mechanisms

In ?? we investigate if knowledge spillovers were intensified when two mines were connected through multiple mechanisms at the same time. We construct knowledge pools where mines in the pool must simultaneously meet two criteria. In column (1) we cannot identify any spillover enhancements between mines in the same mining house that also share a common manager at the usual levels of statistical significance.²² This result is somewhat expected given the high correlation between *Manager Knowledge Pool* and *Org * Manager Knowledge Pool*: all mines connected through a manager interlock were also connected through the same mining house, except for a few independent mines that shared a common manager. Columns (2) and

²¹For example, [Jaffe et al. \(1993\)](#) found stronger knowledge spillovers at the local level than the state level.

²²Although the organizational, managerial, and interacted *org*manager* pools are not significant at conventional levels by themselves, the joint significance test yields an F statistic of 4.68, which implies that at least one of these three mechanisms is important in diffusing cyanide knowledge.

(3) show that close geographical proximity enhances the spillovers coming from managers and organizations. Knowledge spillovers were increased by roughly one quarter to one third if both criteria for connections were met.

[Insert Table 10 Here]

5 Conclusion

We investigate a unique setting and use a novel archival dataset of the South African gold mining industry at the turn of the 20th century. We find strong evidence that technology diffusion took place at both the extensive and intensive margins. We observe substantial productivity gains immediately after adoption of the cyanide ore treatment process. The new method allowed marginally profitable mines to survive and new mines to open. We also find that continuous learning permitted further productivity gains in the longer term. Common ownership and an organizational hierarchy made the transition to the cyanide technology more likely. Mining houses implemented a rollout of the new technology throughout their operating mines. Mining houses also facilitated further development of the technology by appointing engineers and mine managers to oversee multiple affiliated mines. In contrast, we find that administrative personnel such as directors and secretaries were ineffective in transmitting technological knowledge. Mines also learned from their geographical neighbours, but the spillovers were very localized.

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6 Figures

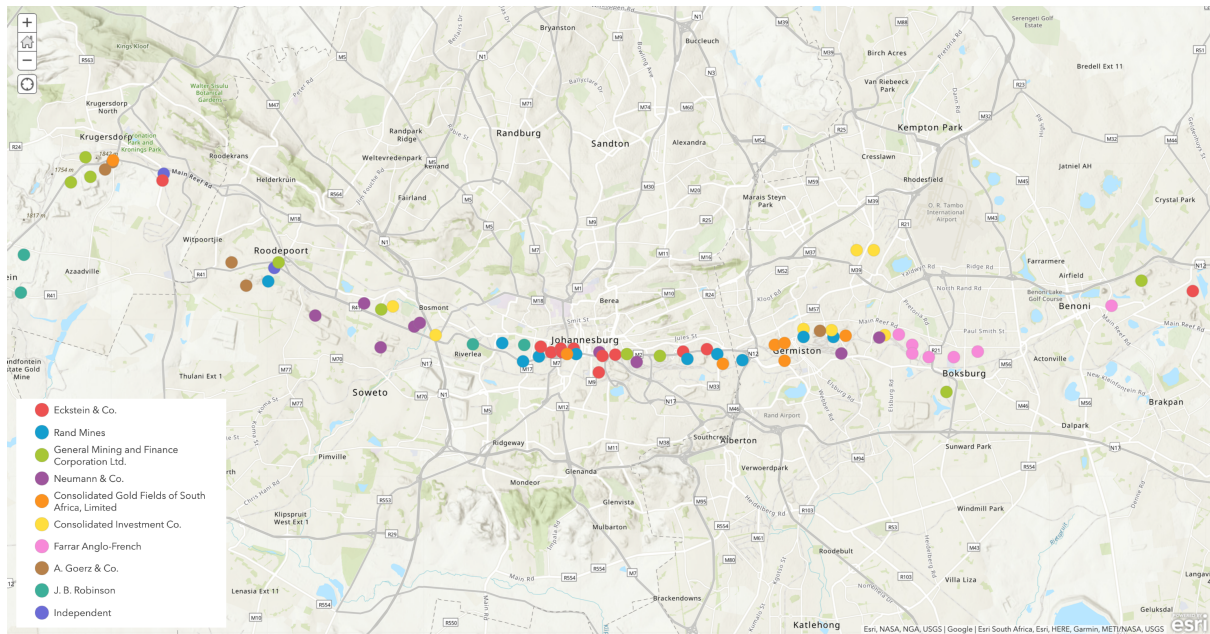


Figure 1: Mine Locations (Witwatersrand District), by Mining House

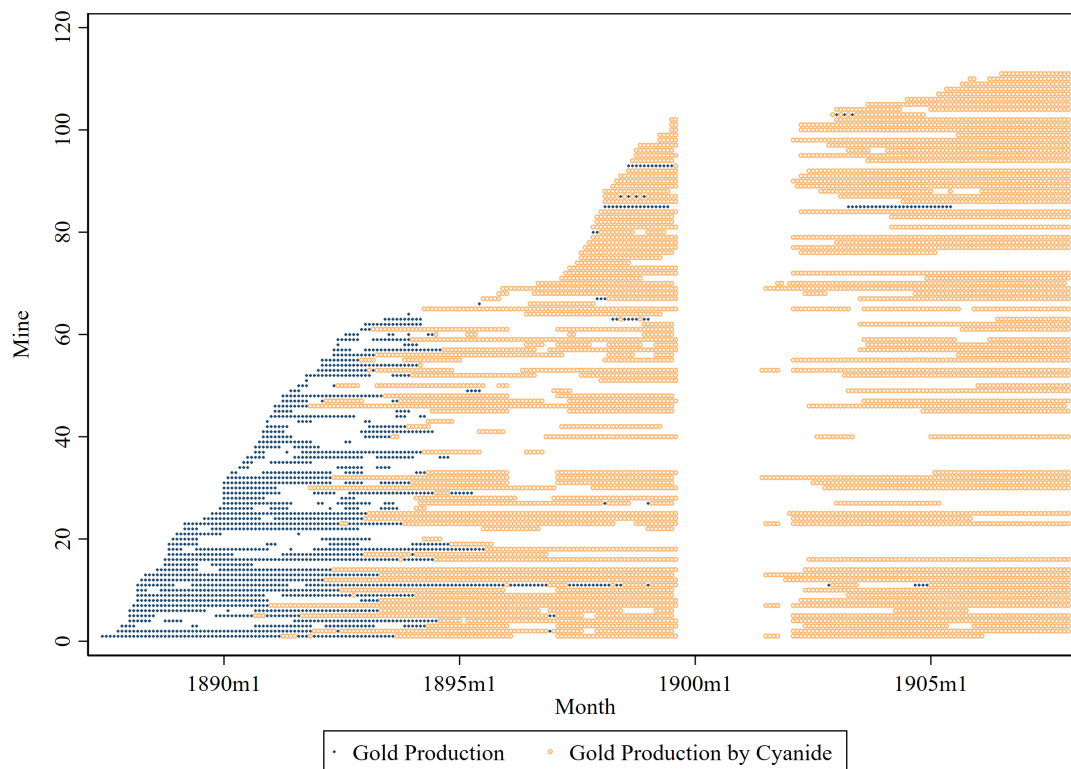


Figure 2: Months of gold production, by mine

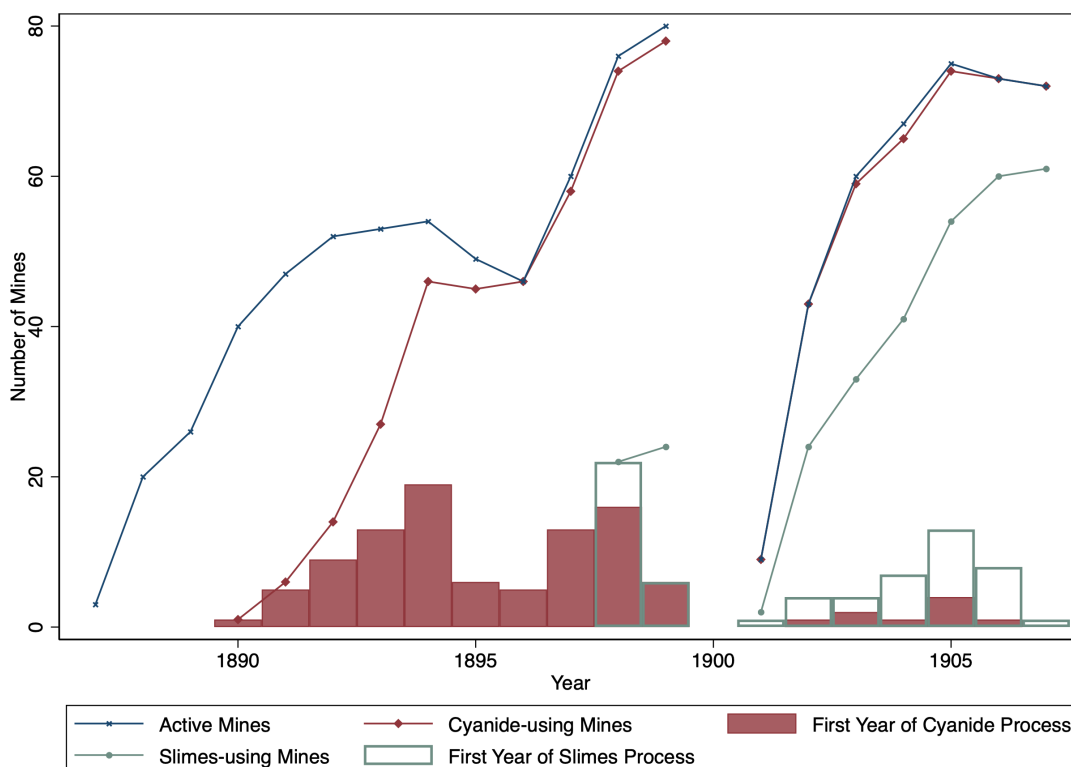


Figure 3: Cyanide Process Adoption

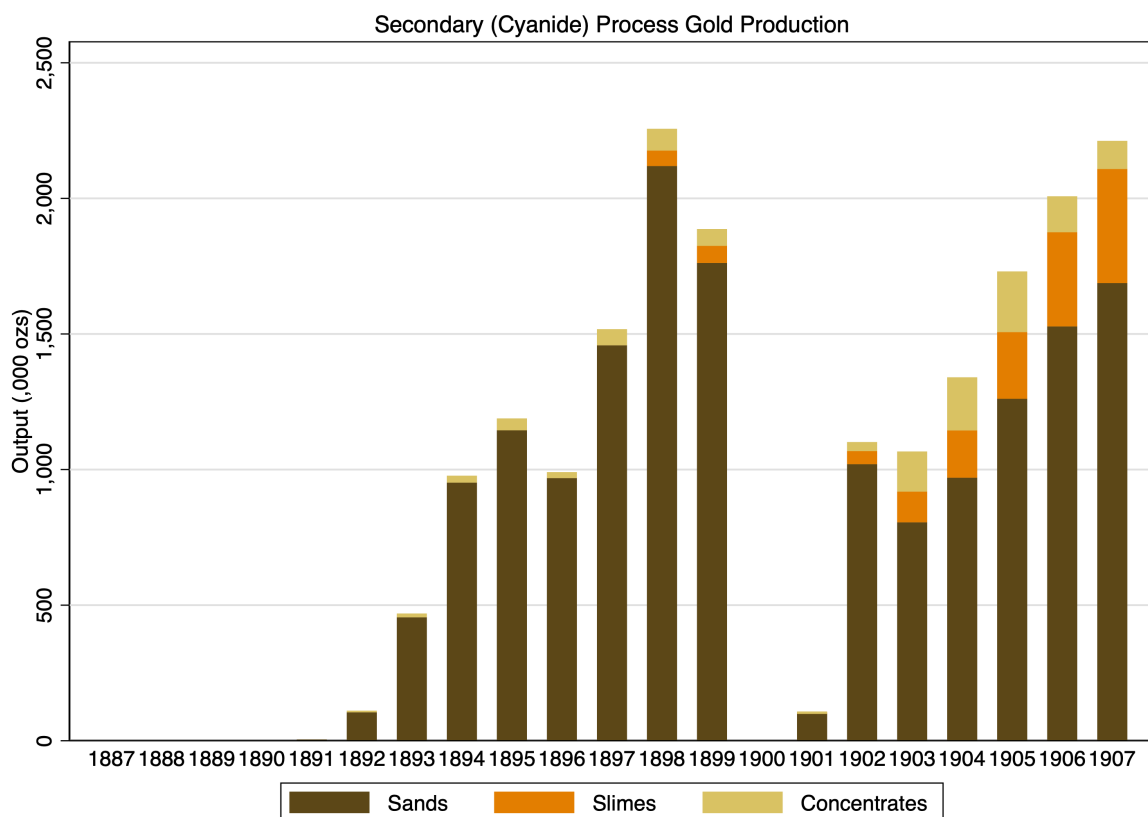
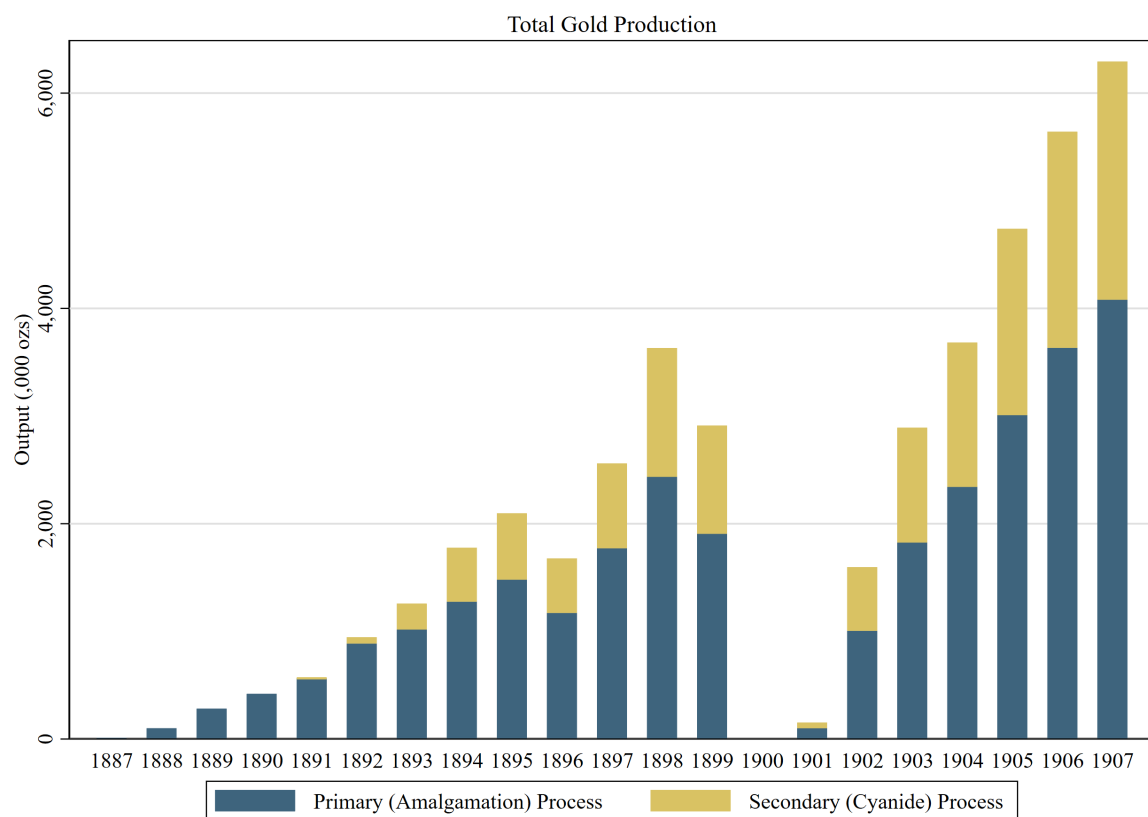


Figure 4: Gold Output, by Process

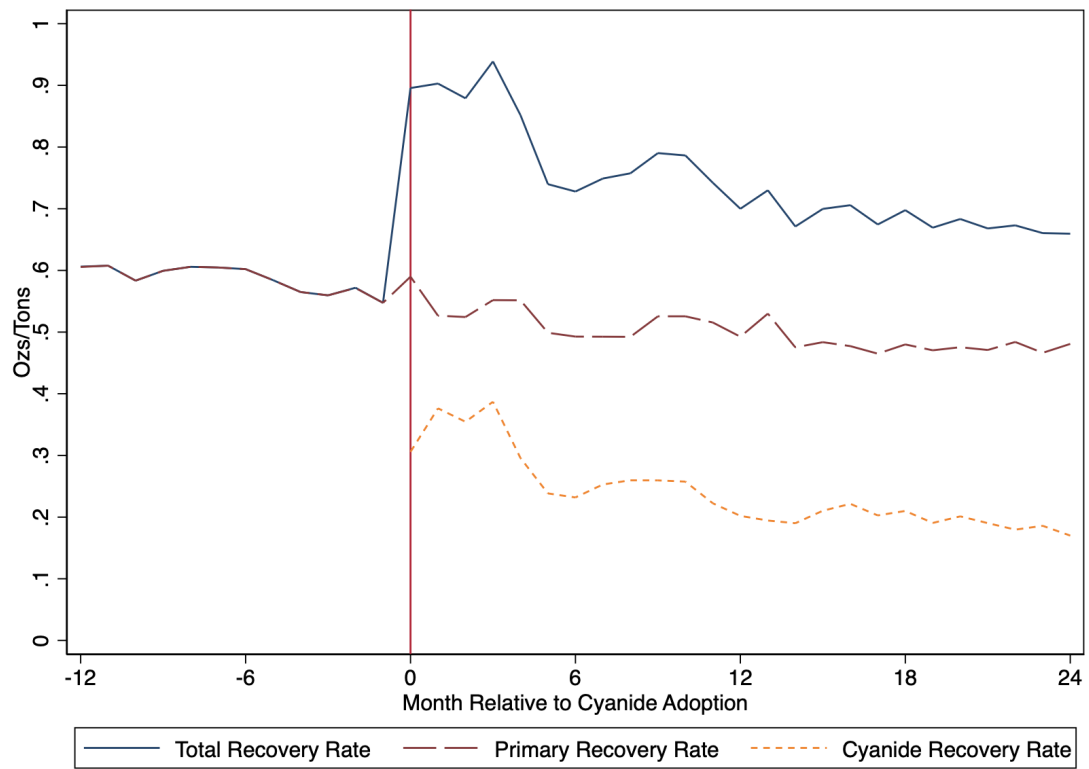


Figure 5: Gold Recovery Rates around Cyanide Adoption (Simple Average)

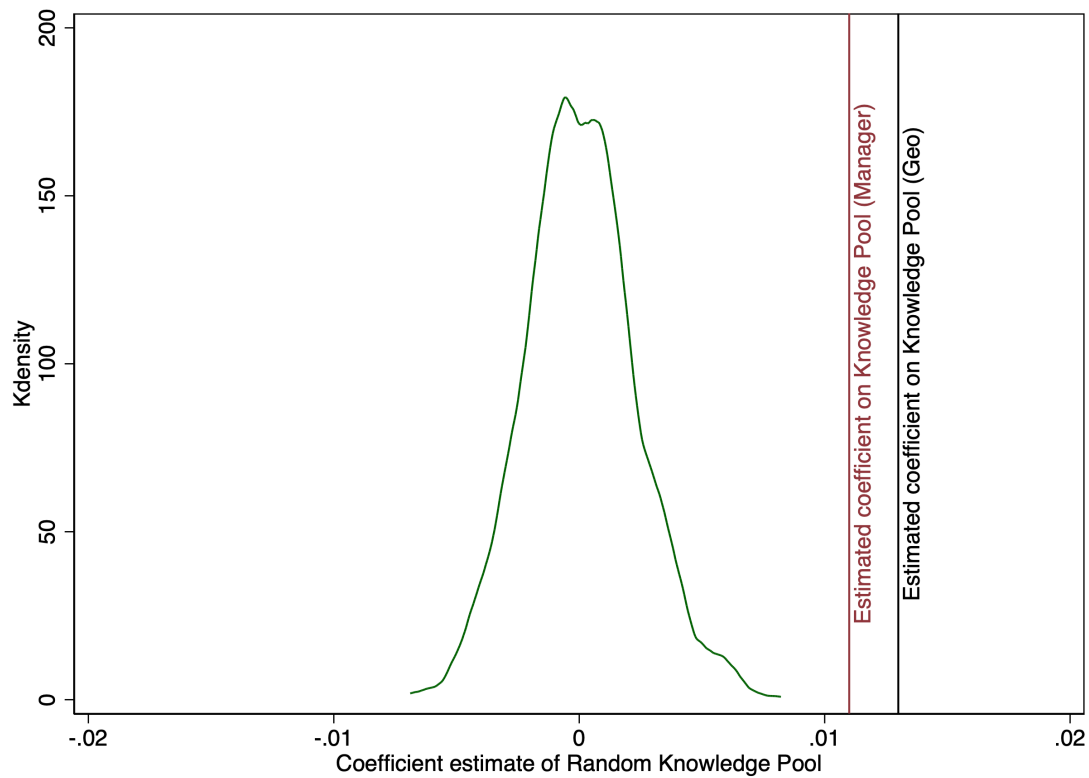


Figure 6: Randomized Inference (N = 1000)

Table 1: Summary Statistics

Each observation is a mine-month. *Primary Recovery Rate* is the ratio of $Ozs^{Primary}$ to $Tons^{Primary}$. *Cyanide Recovery Rate* is the ratio of $Ozs^{Cyanide}$ to $Tons^{Primary}$. *Total Recovery Rate* is the sum of *Primary Recovery Rate* and *Cyanide Recovery Rate*. *Productivity^{Cyanide}* is as derived in subsection 3.2, and is proportional to $Ozs_{i,t}^{Cyanide}/Ozs_{i,t}^{Primary}$. *Cyanide Process* equals one if any of the Sands, Slimes or Concentrates processes were used. *Sands/Slimes/Concentrates Process* equals one if a mine used the sands/slimes/concentrates process in that month and zero otherwise. *CumulativeExtraction* is the cumulative tons of ores used in the primary process in millions of tons. *Business Connection* equals one if a mine had a business relationship with an external cyanide processor in the past 12 months and zero otherwise. *Stoppage* equals one if a mine experienced a temporary stoppage that month and zero otherwise. *Clean-up* equals one if a mine's output was affected by irregular events, such as from the clean-up of the gold extraction equipment and zero otherwise. *By-products* equals one if the gold output contained irregular outputs, such as from by-products, and zero otherwise. *Tailings Used* equals one if previously treated ore was reused in the cyanide process that month and zero otherwise. *Independent mine* equals one if the mine did not belong to a mining house and zero otherwise. *Witwatersrand Mine* equals one if the mine is located in the Witwatersrand area and zero otherwise. *French/German Connection* equals one if a mine had an office in that location and zero otherwise.

Variable	N	Mean	SD	Median	Min	Max
Tons ('000) Primary	9659	9.58	8.46	7.24	0.12	66.2
Ozs ('000) Primary	9659	3.03	2.47	2.38	0.07	18.5
Tons ('000) Cyanide	7458	8.10	5.94	6.30	0.38	47.1
Ozs ('000) Cyanide	7458	1.51	1.06	1.24	0.03	9.52
Primary Recovery Rate	9659	0.41	0.32	0.31	0.03	7.08
Cyanide Recovery Rate	7458	0.15	0.10	0.13	0.01	2.22
Total Recovery Rate	9659	0.54	0.33	0.45	0.06	7.08
Cyanide Productivity	7458	0.48	0.22	0.43	0.16	1.41
Cyanide Process	9659	0.80	0.40	1	0	1
Sands Process	9659	0.77	0.42	1	0	1
Slimes Process	9659	0.33	0.47	0	0	1
Concentrates Process	9659	0.20	0.40	0	0	1
Cumulative Extraction	9659	0.48	0.59	0.27	0	4.50
Business Connection	9659	0.09	0.28	0	0	1
Stoppage	9659	0.005	0.07	0	0	1
Clean-up	9659	0.003	0.06	0	0	1
By-products	9659	0.01	0.11	0	0	1
Tailings Used	9659	0.04	0.19	0	0	1
Independent Mine	9659	0.32	0.46	0	0	1
Witwatersrand Mine	9659	0.96	0.20	1	0	1
#Personnel	9499	11.1	3.21	11	1	22
#Directors	9423	7.98	2.54	8	1	17
#Managers	8045	1.68	0.71	2	1	4
#Secretaries	9428	1.81	0.40	2	1	2
French Connection	9306	0.41	0.49	0	0	1
German Connection	9306	0.09	0.29	0	0	1

Table 2: Diffusion of the Cyanide Process

We run OLS and Hazard models of a mine's adoption of the sands/slimes cyanide process. *Knowledge Pool(m)* is the connection intensity weighted sum of the number of connected sands/slimes-using mines. We drop the French and German knowledge pools in the first two columns because only one mine had a French connection and no mines had German connections in the pre-cyanide period. Observations after the first month of sands/slimes adoption are dropped. For slimes process adoption, we further restrict the sample to cyanide using mines after January 1898, when the slimes process was first reported to the Chamber of Mines, and before 1900, when the second Boer war started. We condition on cumulative extraction and cumulative extraction squared, and lagged own-mine primary recovery rate. Robust standard errors are clustered at the mine and month-year levels. Levels of significance are indicated by *, **, and *** for 10%, 5%, and 1% respectively.

Dependent Variable Sample Period	Sands Adoption 1887m1-1895m12		Slimes Adoption 1898m1-1899m12	
	(1) OLS	(2) Hazard	(3) OLS	(4) Hazard
Knowledge Pool (Org)	0.020*** (0.007)	0.239*** (0.090)	-0.004 (0.003)	-0.559 (0.389)
Knowledge Pool (Manager)	-0.021 (0.057)	-0.335 (0.821)	0.054** (0.026)	1.719*** (0.562)
Knowledge Pool (Geo)	-0.008 (0.006)	-0.221 (0.176)	0.012 (0.012)	0.269 (0.176)
Knowledge Pool (French)			-0.009** (0.003)	-0.496** (0.203)
Knowledge Pool (German)			0.038** (0.017)	2.282*** (0.813)
Lagged Primary Recovery Rate	0.027* (0.015)	1.486*** (0.526)	-0.011 (0.048)	0.932 (1.268)
Observations	1,292	1,296	869	869
Adjusted R-squared	0.063		0.059	
Mine FE	No	No	No	No
Month FE	Yes	Yes	Yes	Yes

Table 3: Cyanide Process Adoption and Gold Recovery Rates

We run OLS regressions of gold recovery rates on *Cyanide Process* and controls, with no allowance for knowledge spillovers. Columns 3 and 6 only use a mine's observations from 12 months before to 12 months after the adoption of cyanide. All variables are as defined in [Table 1](#). Mine and month fixed effects are used in all regressions. Robust standard errors are clustered at the mine and month-year levels. Levels of significance are indicated by *, **, and *** for 10%, 5%, and 1% respectively.

	Total Recovery Rate			Primary Recovery Rate		
	(1) Entire Sample	(2) Entire Sample	(3) Adoption ± 1-Year	(4) Entire Sample	(5) Entire Sample	(6) Adoption ± 1-Year
Cyanide Process	0.268*** (0.053)	0.265*** (0.050)	0.280*** (0.041)	0.033 (0.030)	0.031 (0.028)	-0.001 (0.016)
Cumulative Extraction		-0.054 (0.127)	-0.863 (0.865)		-0.047 (0.119)	-0.053 (0.669)
Cumulative Extraction Sqr		0.021 (0.020)	0.270 (1.666)		0.016 (0.019)	-0.048 (0.994)
Slimes Process		-0.008 (0.025)	0.102** (0.044)		-0.021 (0.021)	0.019 (0.018)
Business Connection		-0.009 (0.019)	0.074*** (0.027)		-0.013 (0.017)	0.057** (0.023)
Observations	9,659	9,659	1,551	9,659	9,659	1,551
Adjusted R-squared	0.577	0.579	0.755	0.622	0.624	0.849

Table 4: Cyanide Productivity and Knowledge Spillovers

We regress cyanide productivity on a knowledge pool(s), mine controls, and mine and month fixed effects. Column (1) to (5) correspond to five knowledge pools: (1) organizational spillovers through membership of a common mining house, (2) spillovers through common mine managers/engineers, (3) spillovers from geographical neighbours, (4) spillovers from mines with French connections, and (5) spillovers from mines with German connections. We define each knowledge pool as the weighted sum of the cyanide productivity of all mines in the pool: $\sum_{c_{ijt}^m=1} g_{ijt}^m K_{jt}$. c_{ijt}^m is a binary variable equal to one if mine j is in mine i 's knowledge pool; g_{ijt}^m is the connection intensity measure; and K_{jt} is the above expectation cyanide productivity of mine j in month t . A mine j is in mine i 's knowledge pool if: both mines are in the same mining house (column 1), both mines share a common manager and/or engineer (column 2), the physical distance between i and j is no greater than 2.5 kilometres (column 3), and both mines have a French/German connection (columns 4/5). Knowledge pools are standardized to be mean zero with a standard deviation of one for ease of interpretation hereafter. All variables are defined in Table 1. Robust standard errors are clustered at the mine and month-year levels. Levels of significance are indicated by *, **, and *** for 10%, 5%, and 1% respectively.

	Cyanide Process						Primary Process
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Knowledge Pool (Org)	0.010*** (0.003)					0.001 (0.003)	-0.006 (0.017)
Knowledge Pool (Manager)		0.015*** (0.003)				0.011*** (0.004)	0.008 (0.006)
Knowledge Pool (Geo)			0.013*** (0.003)			0.013*** (0.003)	0.018 (0.017)
Knowledge Pool (French)				0.005 (0.008)		0.003 (0.008)	-0.022 (0.017)
Knowledge Pool (German)					0.010*** (0.004)	0.008** (0.004)	0.006 (0.007)
Lagged Own Knowledge	0.862*** (0.061)	0.854*** (0.064)	0.863*** (0.062)	0.878*** (0.066)	0.867*** (0.063)	0.835*** (0.058)	-0.124*** (0.023)
Cumulative Extraction	-0.074** (0.035)	-0.082*** (0.030)	-0.086** (0.036)	-0.084** (0.038)	-0.078** (0.037)	-0.087*** (0.031)	0.012 (0.060)
Concentrates Process	-0.100*** (0.010)	-0.101*** (0.011)	-0.102*** (0.010)	-0.100*** (0.010)	-0.103*** (0.010)	-0.104*** (0.010)	-0.022* (0.012)
Slimes Process	-0.047*** (0.013)	-0.043*** (0.011)	-0.046*** (0.012)	-0.045*** (0.013)	-0.041*** (0.013)	-0.041*** (0.011)	-0.012 (0.012)
French Connection	0.033*** (0.012)	0.035*** (0.010)	0.035*** (0.012)	0.027* (0.015)	0.034*** (0.012)	0.030** (0.014)	0.013 (0.032)
German Connection	-0.026 (0.037)	-0.057 (0.039)	-0.015 (0.036)	-0.019 (0.035)	-0.039 (0.037)	-0.071* (0.040)	0.096*** (0.023)
Observations	7,032	6,516	7,032	7,032	7,032	6,516	7,318
Adjusted R-squared	0.720	0.733	0.721	0.718	0.720	0.737	0.747

Table 5: Cyanide Knowledge Spillovers by Personnel Roles

We test for spillovers if the connected person is a (1) previous manager, (2) director, or (3) company secretary. An individual is defined as a previously connected mine manager/engineer if they also worked at another mine in the past three years but not in the current year. The knowledge pools of previous managers, directors, and secretaries are calculated as the weighted sum of the above expectation cyanide productivity of other mines which share historical managers, current directors, and current secretaries with the focal mine. We construct three geographical knowledge pools using mines that were located within a 0-2.5km, 2.5-5km, and 5-10 km radius, respectively. We control for spillovers from all other mechanisms, and we include all control variables as in Table 4. All variable definitions are in Table 1. Mine fixed effects and month fixed effects are included in all columns. Robust standard errors are clustered at the mine and month-year levels. Levels of significance are indicated by *, **, and *** for 10%, 5%, and 1% respectively.

	(1) Personnel Roles	(2) Geographical Distance
Knowledge Pool (Manager)	0.011*** (0.003)	0.011*** (0.004)
Knowledge Pool (Geo 0-2.5km)	0.013*** (0.003)	0.014*** (0.003)
Knowledge Pool (Previous Manager)	-0.000 (0.002)	
Knowledge Pool (Director)	0.005 (0.006)	
Knowledge Pool (Secretary)	0.002 (0.004)	
Knowledge Pool (Geo 2.5-5km)		0.002 (0.003)
Knowledge Pool (Geo 5-10km)		0.005 (0.003)
Observations	6,516	6,516
R-squared	0.748	0.748

Table 6: Technology Leaders and Laggards

We test for knowledge spillovers at technology leaders/laggards. In columns (1) and (2) we divide all mines, year by year, into two groups based on their cyanide productivity: top mines are those with above-median average cyanide productivity in the previous year, and bottom mines are all others. We restrict the sample to mines with at least six months' productivity data in the previous year. In columns (3) and (4) we divide all mines into two groups based on the time of cyanide adoption: veteran mines are those that adopted the cyanide process before or in 1895 and novice mines are those that adopted it after 1895. We estimate columns (3) and (4) with observations from January 1896 onwards. All variable definitions are in Table 1. We include all control variables as in Table 4. Mine fixed effects and month fixed effects are included in all columns. Robust standard errors are clustered at the mine and month-year levels. Levels of significance are indicated by *, **, and *** for 10%, 5%, and 1%, respectively.

	Cyanide Productivity		Cyanide Experience	
	(1) Top	(2) Bottom	(3) Veteran	(4) Novice
Knowledge Pool (Org)	-0.003 (0.005)	-0.007 (0.006)	-0.001 (0.003)	-0.002 (0.009)
Knowledge Pool (Manager)	0.014*** (0.005)	0.014** (0.006)	0.004 (0.003)	0.015* (0.008)
Knowledge Pool (Geo)	0.001 (0.003)	0.018** (0.007)	0.007*** (0.003)	0.014** (0.005)
Knowledge Pool (French)	-0.013 (0.009)	0.000 (0.012)	-0.002 (0.007)	0.037 (0.023)
Knowledge Pool (German)	0.003 (0.003)	0.007* (0.003)	0.006** (0.003)	0.015* (0.009)
Observations	2,480	2,420	3,433	2,364
R-squared	0.819	0.728	0.773	0.778
	Interact All Variables		Interact Knowledge Pools Only	
	(1) Bottom	(2) Novice	(3) Bottom	(4) Novice
Bottom x Knowledge Pool (Org)	-0.004 (0.007)		-0.005 (0.006)	
Bottom x Knowledge Pool (Manager)	0.000 (0.007)		0.003 (0.007)	
Bottom x Knowledge Pool (Geo)	0.016* (0.009)		0.011** (0.005)	
Bottom x Knowledge Pool (French)	0.014 (0.017)		0.005 (0.006)	
Bottom x Knowledge Pool (German)	0.004 (0.005)		-0.003 (0.005)	
Novice x Knowledge Pool (Org)		-0.001 (0.010)		0.004 (0.009)
Novice x Knowledge Pool (Manager)		0.011 (0.008)		0.009 (0.009)
Novice x Knowledge Pool (Geo)		0.006 (0.006)		0.004 (0.007)
Novice x Knowledge Pool (French)		0.038 (0.024)		-0.013 (0.009)
Novice x Knowledge Pool (German)		0.010 (0.009)		0.006 (0.008)
Observations	4,900	5,797	4,900	5,797
Adjusted R-squared	0.767	0.764	0.748	0.752

Table 7: Robustness

We replicate Table 4 using alternative definitions of cyanide productivity and cyanide knowledge pools. All variable definitions are in Table 1. Mine fixed effects and month fixed effects are included in all columns. Robust standard errors are clustered at the mine and month-year levels. Levels of significance are indicated by *, **, and *** for 10%, 5%, and 1% respectively.

Panel A	$K_{jt} = n\text{-month Avg. above Expectation Productivity}$		
	(1) 3-month Avg. Knowledge	(2) 6-month Avg. Knowledge	(3) 12-month Avg. Knowledge
Knowledge Pool (Org)	-0.003 (0.004)	-0.006 (0.004)	-0.010* (0.006)
Knowledge Pool (Manager)	0.010** (0.004)	0.012** (0.005)	0.012** (0.005)
Knowledge Pool (Geo)	0.011*** (0.003)	0.006** (0.003)	0.002 (0.003)
Knowledge Pool (French)	0.003 (0.007)	0.001 (0.007)	0.005 (0.008)
Knowledge Pool (German)	0.006* (0.003)	0.006* (0.004)	0.005 (0.004)
Observations	6,240	5,821	5,033
Adjusted R-squared	0.745	0.722	0.701
Panel B	Multiple Cyanide Processes		
	(1) Sands & Slimes	(2) Sands & Concentrates	(3) Sands, Slimes, & Concentrates
Knowledge Pool (Org)	0.001 (0.003)	0.003 (0.003)	0.003 (0.003)
Knowledge Pool (Manager)	0.012*** (0.004)	0.012*** (0.004)	0.013*** (0.004)
Knowledge Pool (Geo)	0.012*** (0.003)	0.012*** (0.003)	0.010*** (0.003)
Knowledge Pool (French)	0.003 (0.008)	-0.001 (0.008)	-0.000 (0.008)
Knowledge Pool (German)	0.006 (0.004)	0.010** (0.004)	0.008** (0.004)
Observations	6,516	6,516	6,516
Adjusted R-squared	0.763	0.699	0.742
Panel C	Cyanide Productivity Measure		
	(1) $Ozs^{Cyanide}/Tons^{Cyanide}$	(2) $Ozs^{Cyanide}/Tons^{Primary}$	(3) $\frac{Ozs^{Cyanide}/Tons^{Cyanide}}{Ozs^{Primary}/Tons^{Primary}}$
Knowledge Pool (Org)	0.002 (0.002)	0.002 (0.002)	0.003 (0.004)
Knowledge Pool (Manager)	0.003*** (0.001)	0.004*** (0.001)	0.009** (0.004)
Knowledge Pool (Geo)	0.001 (0.002)	0.005*** (0.002)	0.007** (0.003)
Knowledge Pool (French)	0.004 (0.004)	0.001 (0.003)	0.010 (0.010)
Knowledge Pool (German)	0.002 (0.001)	0.002 (0.001)	0.006 (0.004)
Observations	6,516	6,516	6,516
Adjusted R-squared	0.784	0.714	0.763

Table 7: Robustness (Continued)

Panel D	Knowledge Pool Construction			
	(1)	(2)	(3)	(4)
	Incumbent Mines	Dynamic	Max Knowledge	Log-log Model
	Registered before 1890	Estimation	Pool $\max(K_{jt} c_{ijt} = 1) \times g_{ijt}$	$\sum c_{ijt} g_{ijt} \log(K_{jt})$
Knowledge Pool (Org)	0.001 (0.003)	0.001 (0.003)	0.002 (0.003)	0.000 (0.002)
Knowledge Pool (Manager)	0.005 (0.004)	0.008** (0.004)	0.012*** (0.003)	0.007*** (0.002)
Knowledge Pool (Geo)	0.013*** (0.004)	0.016*** (0.003)	0.011*** (0.002)	0.008*** (0.002)
Knowledge Pool (French)	-0.001 (0.010)	0.002 (0.008)	-0.004 (0.007)	0.004 (0.005)
Knowledge Pool (German)	0.006 (0.004)	0.010** (0.004)	0.010** (0.004)	0.005* (0.003)
Observations	4,107	6,516	6,516	6,516
Adjusted R-squared	0.738	0.736	0.738	0.732
Panel E	Alternative Connection Intensity g_{ijt}			
	(1)	(2)	(3)	(4)
	Unweighted	Linear	Square	Polynomial
	Knowledge Pool $g_{ijt} = 1$	Transformation $f(x) = x$	Transformation $f(x) = x^2$	Transformation $f(x) = -x^2 + 2x$
Knowledge Pool (Org)	0.000 (0.003)	0.002 (0.003)	0.004 (0.003)	0.001 (0.003)
Knowledge Pool (Manager)	0.012*** (0.004)	0.010*** (0.004)	0.007** (0.003)	0.011*** (0.004)
Knowledge Pool (Geo)	0.013*** (0.003)	0.013*** (0.003)	0.011*** (0.003)	0.013*** (0.003)
Knowledge Pool (French)	0.003 (0.008)	0.004 (0.008)	0.004 (0.008)	0.003 (0.008)
Knowledge Pool (German)	0.008** (0.004)	0.008* (0.004)	0.007* (0.004)	0.008** (0.004)
Observations	6,516	6,516	6,516	6,516
Adjusted R-squared	0.737	0.736	0.735	0.737

Appendix A Tables

Table A1: Mining House Affiliation

Mining House	Founded	Entrepreneurs	Operating Mines
A. Goerz and Co.	1897	Adolf Goerz	Geduld Proprietary, Lancaster, Lancaster West, May Consolidated, Princess Estate, Roodepoort Central Deep
Consolidated Goldfields of South Africa	1887		Jupiter, Knights Deep, Luipaardsvlei, Nigel Deep, Robinson Deep, Simmer and Jack, Simmer and Jack East, Simmer Deep
Johannesburg Consolidated Investment Co.	1889	Barney Barnato	Balmoral, Knight's, New Croesus, New Spes Bona, Buffelsdorn, Consolidated Langlaagte, Ginsberg, Glencairn, Langlaagte Royal, New Heidelberg Roodepoort, New Primrose, New Rietfontein, Unified Main Reef, Rietfontein A, Roodepoort Kimberley
Eckstein and Co. (Corner House Group)	1888	Hermann Eckstein, Alfred Beit	Bonanza, City and Suburban, Crown Reef, New Heriot, New Modderfontein, Ferreira, French Rand, Henry Nourse, Robinson, Robinson Central Deep, Village Deep, Village Main Reef
Farrar Anglo-French		George Farrar	Angelo, New Blue Sky, New Kleinfontein, Cason, Driefontein Consolidated, East Rand Proprietary, Langlaagte United, New Comet
General Mining and Finance Corporation	1895	George Albu, Leopold Albu	Aurora West, Cinderella Deep, New Goch, Meyer and Charlton, Rand Nigel, Roodepoort United Main Reef, Van Ryn, Van Ryn West, Violet, West Rand Consolidated, West Rand Mines, Steyn Estate
J. B. Robinson Group		Joseph Robinson	Langlaagte Block B, Porges Randfontein, Langlaagte Estate, Langlaagte Star, North Randfontein, Robinson Randfontein, South Randfontein
Neumann and Co.		Sigismund Neumann	Bantjes, Consolidated Main Reef, Knights Central, Main Reef, Main Reef West, Treasury, Vogelstruis Consolidated, Witwatersrand Deep, Wollhunter
Rand Mines		Hermann Eckstein, Alfred Beit	Crown Deep, Durban Roodepoort Deep, Ferreira Deep, Geldenhuis Deep, Glen Deep, Jumpers Deep, Langlaagte Deep, Nourse Deep, Paarl Central, Rose Deep

Appendix B Cyanide Productivity Derivation

We derive the cyanide productivity based on the following three simplifying assumptions:

1. Percentage of gold that can be recovered by mercury amalgamation is a

Table A2: Cyanide Productivity Estimation

We run OLS regressions of cyanide productivity on its potential determinants. All variables are as defined in Table 1. Mine and month fixed effect are used in all regressions. t-statistics based on robust standard errors are clustered at the mine and month-year levels are in parentheses. Levels of significance are indicated by *, **, and *** for 10%, 5%, and 1% respectively.

	(1) Sands	(2) Sands & Slimes	(3) Sands & Conc.	(4) Sands & Slimes & Conc.
Cumulative Extraction	-0.049*** (0.017)	-0.079*** (0.018)	-0.043** (0.017)	-0.073*** (0.018)
Cumulative Extraction Squared	0.005 (0.004)	0.010** (0.004)	0.002 (0.004)	0.007 (0.004)
Concentrates Process	-0.104*** (0.006)	-0.105*** (0.006)	0.012** (0.006)	0.010 (0.006)
Slimes Process	-0.060*** (0.007)	0.045*** (0.007)	-0.058*** (0.007)	0.046*** (0.008)
Business Connection	-0.001 (0.008)	-0.002 (0.008)	-0.005 (0.008)	-0.007 (0.008)
Stoppage	0.025 (0.027)	0.013 (0.029)	0.028 (0.027)	0.016 (0.029)
Clean-up	0.085*** (0.030)	0.085*** (0.032)	0.079** (0.031)	0.077** (0.033)
By-products	0.016 (0.015)	0.013 (0.016)	0.009 (0.015)	0.007 (0.016)
Tailings Used	-0.022** (0.010)	-0.036*** (0.010)	-0.030*** (0.010)	-0.044*** (0.011)
Observations	7,454	7,454	7,454	7,454
Adjusted R-squared	0.526	0.566	0.490	0.551

2. Percentage loss of gold ore from primary to cyanide process is b

3. Percentage of gold in tailings that are sorted into sands is c

Based on the first assumption, the gold in crushed ores can be written as:²³

$$O_{zs}^{in\ ores*} = \frac{O_{zs}^{Primary}}{a}$$

Then, given assumption 2, the gold left in the tailings would be $(1 - b)$ multiplied by the difference between the gold in crushed ores and the gold recovered from crushed ores:

$$O_{zs}^{in\ tailings*} = (1 - b) \times (O_{zs}^{in\ ores*} - O_{zs}^{Primary}) = \frac{(1 - a)(1 - b)}{a} O_{zs}^{Primary}.$$

With the last assumption, the gold sorted into sands would be c multiplied by the gold in tailings:

$$O_{zs}^{in\ sands*} = c \times O_{zs}^{in\ tailings*} = \frac{c(1 - a)(1 - b)}{a} O_{zs}^{Primary}.$$

²³Mine and time subscripts are dropped for simplicity

Therefore, cyanide productivity can be written as:

$$Productivity^{Cyanide} = \frac{OzS^{Cyanide}}{OzS^{in\ sands*}} = \frac{a}{c(1-a)(1-b)} \times \frac{OzS^{Cyanide}}{OzS^{Primary}} \propto \frac{OzS^{Cyanide}}{OzS^{Primary}}.$$

Since a , b , and c are constant, the cyanide productivity is proportional to the ratio between the gold yield in the cyanide process and the gold yield in the primary process. We use this ratio as the empirical measure of cyanide productivity.

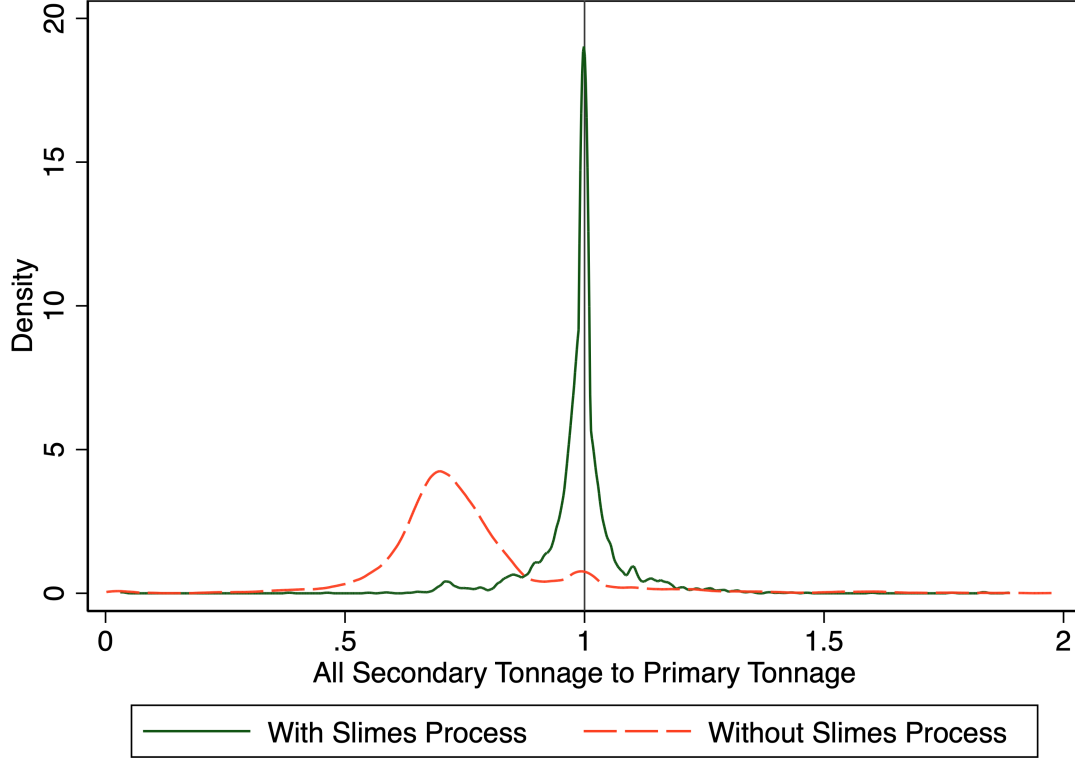


Figure B1: Proportion of Tailings Went to Secondary Processes