Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_00923

Ownership and Productivity in Vertically-Integrated Firms: Evidence from the Chinese Steel Industry

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April 17, 2020

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Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_00923

Abstract

We study productivity differences in vertically-integrated steel facilities using equipment-level information on inputs and output for each of the main stages in the value chain. We obtain stage-level productivity estimates by estimating a multi-stage production system and then integrate them into estimates for integrated facilities. At this level, we do not find statistically significant differences in productivity by ownership. This conceals important differences upstream and downstream in the value chain: Private firms outperform in pig-iron and steel-making, but lag in sintering. Inferior access to higher quality raw materials and use of less automated technology are likely sources of these differences.

Key Words: Total Factor Productivity, Vertically-Integrated, Steel, SOEs, Private, China

JEL Classifications: D24 L11 L23 L61

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1 Introduction

Increases in productivity are an important source of economic growth for firms, industries and countries. Researchers have documented sizeable and persistent productivity differences between producers and identified their elimination as a potentially important source of productivity growth.[1] Obtaining accurate measures of productivity however is often hindered by issues of endogeneity and measurement.[2] Productivity analysis is also usually carried out at the aggregate firm level; in contrast, production activity of firms often involves vertically integrated operations carried out in multiple production units in which technologies and productivity likely differ by stage of production. Aggregate data miss this dimension and may result in biased estimates of the underlying production technology and firm-level productivity.

In the context of China's vertically integrated steel producers, this paper investigates the sources of productivity differences between production facilities through the lens of their internal structure. As far as we know, this paper is one of the first to investigate these kinds of links.[3] By fact of its size - the sector now produces half of the world's steel - China's steel industry is important both domestically and internationally. The sector also remains heavily state-dominated. A recent literature documents sizeable productivity differences between firms and sectors in China that appear tied to ownership and the regulatory environment.[4] State-owned enterprises (SOEs) often enjoy better access to capital, technology, inputs and

[1]See, for example, Syverson (2004) and Hsieh and Klenow (2009).

[2]See, for example, De Loecker and Goldberg (2014).

[3]There is a literature looking at links between productivity and vertical integration of firms, in which the degree of vertical integration is endogenous. See for example, Hortaçsu and Syverson (2007), Forbes and Lederman (2010), Atalay et al. (2014), Natividad (2014) and Li et al. (2016). In this context, production technologies can still differ by stage of production, and aggregation of productivity across these stages remains an issue.

[4]See for example Hsieh and Klenow (2009), Hsieh and Song (2015), Brandt (2015) and

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human resources, but are also tasked with non-economic objectives and typically operate under softer-budget constraints.

We draw on a unique data set to examine differences in the internal configuration and productivity of steel facilities in China. Detailed input and output data at the equipment level allow us to obtain production function estimates for the three main stages in steel's value chain (sintering, pig-iron making and steel making) as part of a multi-stage production system. The use of input and output in physical units helps eliminate price biases in the estimation (Li et al. (2017)). Following Domar (1961), we then integrate our productivity estimates for each stage into estimates for integrated facilities, using as weights either the estimated elasticities of material inputs in pig-iron making and steel making or the ratio of the value of sinter and pig-iron to steel. The richness of our data allows us to measure the efficiency of producers at the integrated facility level, and more important, to decompose differences in performance by ownership type into process (stage) level differences.

These data reveal systematic differences in the size and internal configuration of steel making facilities by ownership. Central SOEs operate the largest facilities, which on average are more than twice as large as those of private firms, and a third larger than the facilities of provincial SOEs. These differences are accompanied by systematic differences in the number and size of the equipment and furnaces used by firms as the size of an integrated facility increases. Central state-owned facilities consistently operate the smallest number of machines/furnaces in each size category, followed by provincial state-owned and then private facilities. Alternatively, as SOEs build larger integrated facilities, they do so using machines/furnaces of larger average size compared to private firms.

At the facility level, we do not find statistically significant differences in productivity by ownership. Analysis at this level conceals however important differences upstream and downstream in the value chain. Private firms enjoy significant productivity advantages of 6.1 percent in both downstream production stages (pig-iron making and steel making) that

Berkowitz et al. (2017).

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https://doi.org/10.1162/rest_a_00923

are offset by their 10.8 percent lower productivity upstream in sintering. Likely underlying the gap in sintering is central state-owned facilities' superior access to higher quality raw materials, e.g. iron ore, and private firms' use of more labor-intensive, less automated technology. Improved access to raw materials could eliminate the differences in productivity in sintering and result in a statistically significant premium of private firms at the facility level.

The remainder of the paper is organized as follows. Section 2 provides background and context on China's steel sector and industrial policy spanning the period of our analysis. Section 3 describes the data and presents key facts that help guide the empirical analysis. We provide an empirical approach to identify multi-stage productivity in Section 4, followed by a discussion of productivity differences and their underlying sources in Section 5. We discuss potential biases resulting from measurement errors in Section 6 and conclude in Section 7.

2 Background and Context

2.1 China's Steel Sector

By the late 1990s, two decades of double-digit annual growth had made China the world's largest steel producer. In 2015, China produced 803.8 million metric tons of crude steel, accounting for 49.6 percent of the world's total production.[5] Several features of China's steel sector figure prominently in our analysis and distinguish it from that in other countries.[6]

First, the sector is state-dominated. Although the role of the private sector has expanded over time, nearly half of industry output continues to be produced by state-owned firms. In addition, 8 out of the top 10 firms in 2015 were state-owned.[7] Restrictions on foreign firm

[5]Data source: Steel Statistical Yearbook 2018. World Steel Association.

[6]For additional background and analysis of China's steel sector since the late 1970s, see Song and Liu (2012).

[7]Data Source: Top 100 Global Steel Producers (2011-2016). https://www.kaggle.com/

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https://doi.org/10.1162/rest_a_00923

entry and M&A activity have also severely limited the role of foreign-invested enterprises in China's steel sector.

Second, concentration ratios in the domestic industry are low. Despite having half of the worlds' 10 largest steel producers, the production share of the four largest steel producers in China in 2015 was only 19 percent, compared to shares of 65 percent, 78 percent, and 83 percent in the U.S., EU, and Japan, respectively.[8] Low concentration ratios have been accompanied by chronic problems of excess capacity in the sector.

Third, the activity of steel firms in China is largely directed to the production of lower quality steels such as rebar, wire rods and plates for the rapidly expanding domestic market. In 2015, for example, 90 percent of output was sold domestically, nearly two-thirds of which were lower quality products.[9] Domestic firms appear to be heavily protected, and in 2015 imports represented only 1.2 percent of domestic consumption. In sharp contrast, China's steel sector is highly dependent on iron ore imports, and in 2013 two-thirds of the iron ore used was imported. China's iron ore imports also represent two-thirds of global iron ore imports.[10]

Finally, in contrast to the prominent role of electric arc furnaces and the rapid diffusion of mini-mill technology in the U.S. and other countries, steel in China is primarily produced using blast furnaces together with basic oxygen furnaces in vertically integrated facilities.

drubal/top-100-global-steel-producers-20112016

[8]Based on authors' calculations using data from Top 100 Global Steel Producers (2011-2016). https://www.kaggle.com/drubal/top-100-global-steel-producers-20112016 The CR4 ratio for the U.S. is based on data from Top Steelmakers in 2017. World Steel Association.

[9]Although exports were only 10 percent of total domestic production, they presented more than a fifth of total world exports. Data source: China Steel Yearbook 2016, 2017. China Iron and Steel Association. Steel Statistical Yearbook 2018. World Steel Association.

[10]Data source: Steel Statistical Yearbook 2016, 2017, and 2018. World Steel Association.

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This reflects both limited access to scrap materials domestically and a pronounced policy tilt towards larger furnaces and facilities. Less than 10 percent of China's steel is currently produced using electric arc furnaces.[11] In the U.S. and other countries, the adoption of mini-mill technology has been an important source of industry-wide productivity gains.[12]

2.2 Chinese Industrial Policy

A major objective of Chinese industrial policy has been the development of domestic capabilities in sectors identified as key or strategic. Originally, this was largely limited to more mature sectors such as steel, electrical machinery, autos, etc., but more recently has come to include newly emerging technologies such as AI, electric vehicles, renewable energy, biotechnology, etc. In these efforts, central government leadership in identifying key sectors and technologies, concentration of innovation resources in large SOEs, and more recently, the promotion of "indigenous" innovation figure prominently (Brandt and Rawski (2019)). Preferential access to land and finance, subsidies, as well as strict restrictions on the form of participation of foreign firms have been important policy instruments.[13]

China's steel sector has consistently been one of the key targets of China's industrial policy. Major policy documents for the sector include "Development Policies for the Iron and Steel Industry" (2005), "Blueprint for the Adjustment and Revitalization of the Steel

[11] Data source: Steel Statistical Yearbook 2018. World Steel Association.

[12] For the U.S., see Collard-Wexler and De Loecker (2015). Hendel and Spiegel (2014) documents the source of productivity improvement in the context of a single Israeli steel mini-mill.

[13] There is now a small but growing empirical literature on the impact of these and related policies. See, for example, Haley and Haley (2013) and Kalouptsidi (2017) in the case of subsidies; Berkowitz et al. (2017) on the role of access to finance; and Aghion et al. (2015) on the use of subsidies combined with cheap loans, tax holidays, and tariffs, etc. Li et al. (2015) and Liu (2018) try to rationalize these policies in the context of inter-sector linkages, especially upstream-downstream, and market imperfections.

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Industry" (2009) and "Planning for the Adjustment and Upgrading of the Iron and Steel Industry 2016-2020". Facing chronic excess capacity, these documents lay out plans for both technology upgrading, and industry restructuring and consolidation that aim to foster the development of a few national champions in the industry. "Made in China 2025" (2015), the centerpiece of China's current industrial policy, highlights the need to deepen structural reform in the steel industry, with particular emphasis on cutting excess capacity, moving up the value chain, better leveraging economies of scale, and building steel firms with core competitiveness.

3 Data and Descriptive Evidence

3.1 Steel Production Technology

Vertically-integrated steel production involves a complex series of individual processes that use coal as the primary energy source and iron ore as the basic raw material (Ahlbrandt et al. (1996)). A steel facility integrates production carried out in four major stages along the production chain: sintering, pig-iron making, steel making and steel rolling (see Figure 1). Sintering is basically a pre-treatment process that transforms iron ore fines into a high quality burden called sinter for use in the iron-making facility - the blast furnace. The principle of sintering involves the heating of iron ore fines along with flux and coke fines or coal to produce a semi-molten mass that solidifies into porous pieces of sinter with the size and strength necessary for feeding into the blast furnace. It is basically an agglomeration process achieved through combustion.[14] Sinter, together with coke, pulverized coal and limestone are then fed into the top of a blast furnace, while hot air is injected from below, setting off a chemical reaction throughout the furnace as the material moves downward.[15] The molten pig-iron from the blast furnace along with oxygen and fuel are then fed into a basic oxygen furnace to produce steel, which is called primary steel making. Modern steel making can

[14] See more details in Fernández-González et al. (2017).

[15] https://en.wikipedia.org/wiki/Blast-furnace

Review of Economics and Statistics Just Accepted MS.
https://doi.org/10.1162/rest_a_00923

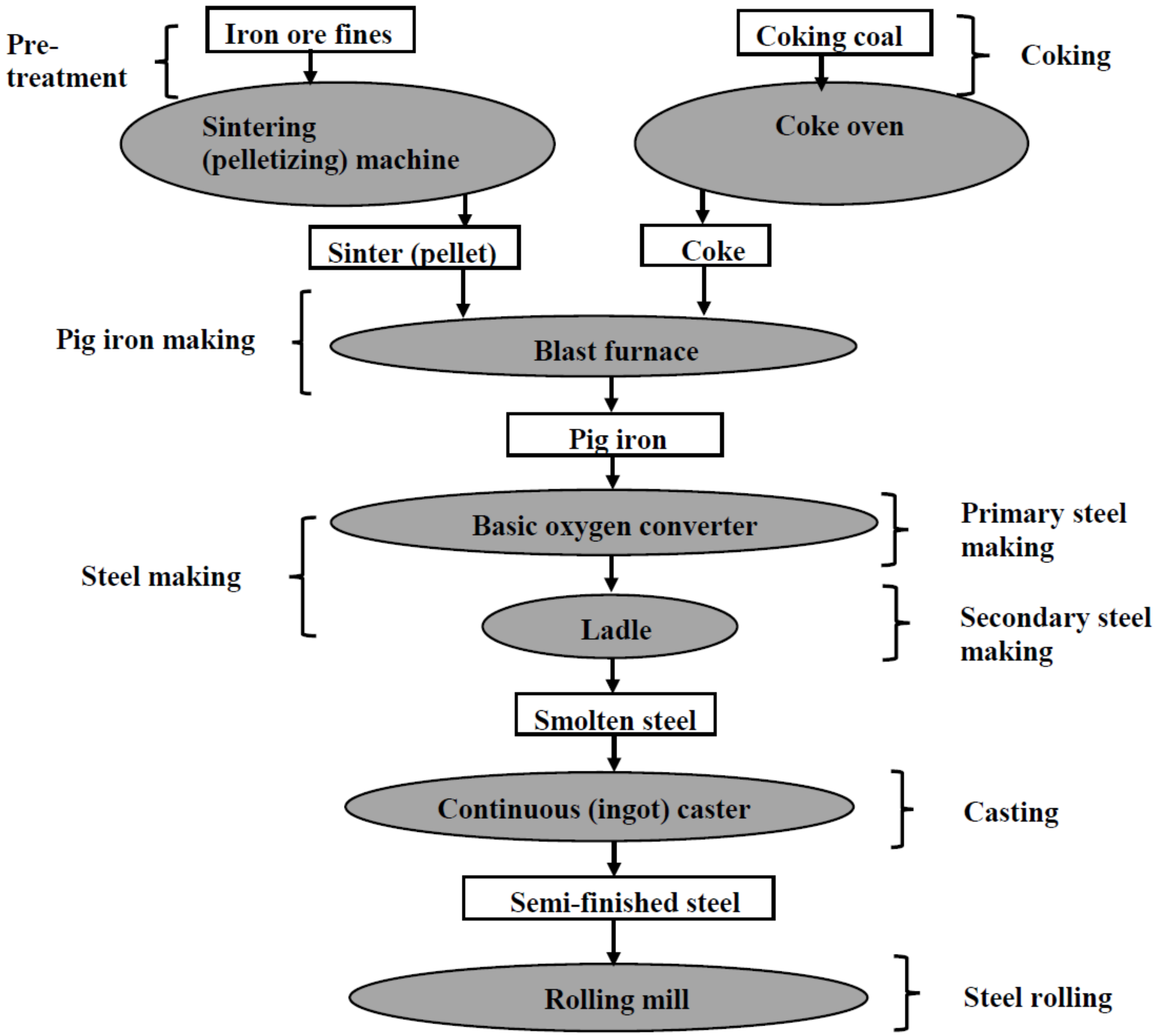

Figure 1: Steel Technology of Integrated Facilities

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also incorporate a secondary steel making process, which involves refining of the crude steel to ensure a higher quality end product.[16] The semi-finished steel produced in vertically-integrated firms is finally shaped into sheets, bars, wire, and tube steel of desired thickness and uniformity through a metal forming process in rolling mills.[17]

Technologically, larger blast furnaces are more efficient as they incur smaller heat losses and enable more efficient heat recovery. However, larger furnaces require higher-grade iron ore. The use of low-grade ore in larger blast furnaces increases energy intensity, generates more waste, and may even shorten the life expectancy of the blast furnaces. Larger basic oxygen furnaces also have clear technological advantages. The utilization of automatic control and monitoring systems improves energy efficiency. In addition, the use of hybrid blowing technology helps to reduce the consumption of material inputs while better design and maintenance of refractory linings contribute to longer life expectancies of the furnaces.[18]

3.2 Data

We construct a unique monthly-level data set on the facilities of vertically-integrated firms in the Chinese steel industry from January 2009 to October 2011.[19] Over this period, production of reporting firms in our sample represents sixty percent of the total steel output in China.[20] The reported data are in the form of equipment-level information on inputs and

[16] http://en.wikipedia.org/wiki/Steelmaking

[17] https://en.wikipedia.org/wiki/Rolling-(metalworking)

[18] See Yu (2001) and Wang et al. (2006) for more details.

[19] The underlying data are collected by the Chinese Iron and Steel Association (CISA) as part of regular data collection efforts from all firms with annual steel production over 1 million tons.

[20] Our data covers most of the production of the SOEs and in upwards of a third of private firms. Missing is the production of smaller non-member private firms, and more important, the output of some member private firms. Notable omissions include Shandong Rizhao Steel, with an annual production capacity of 10 million tons. Also excluded are facilities run by

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outputs in physical units for each of the three major stages of production (sintering, pig-iron making and steel making). Input information includes key material inputs, standardized energy consumption, number of workers, size of equipment (capacity) and utilization rates.[21] These data are supplemented by information on ownership, year of establishment and location.

Our analysis centers on the first three major stages of production and excludes steel rolling. We do so for several reasons. First, finished rolled steel products can be highly differentiated, and differ in value added, final usage, and price. Output however is only reported in physical terms. Second, we only have data on total production of rolled products at the firm level rather than the product or the plant level. The input information is similarly aggregated across products and plants. And third, while the main purpose of sintering and pig-iron making is to meet the immediate consumption needs of the next stage in the production chain, firms often sell or hold inventory in semi-finished steel for later use. Therefore, between steel making and rolling, there is a dynamic dimension to decision-making that our data cannot capture. Despite this omission, we still capture a high percentage of the activity in the sector. In an average steel firm, the total value-added generated by the three stages under our consideration is more than double that of the rolling stage, or nearly seventy percent overall.[22]

Steel production in China is a highly vertically-integrated activity. We are able to link equipment across stages and thereby identify vertically-integrated facilities. At the sinter-iron-steel level, we compiled data on 136 fully vertically-integrated facilities, operated by

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the headquarters of Baosteel, a central SOE that is generally acknowledged to be the most technically advanced steel firm in China.

[21]For steel rolling, we only have aggregate firm level information.

[22]We base these calculations on a 2015 report by the China Mingsheng Bank, "Research on the Steel Industry and Suggestions on Development Strategy".

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59 firms.[23] Figure A1 in the Online Appendix provides an illustration of the make-up of a typical firm in our sample: Each firm may operate multiple integrated facilities; in addition, at each stage in the value chain, a firm may operate multiple production units, i.e. sintering machines, blast furnaces or basic oxygen furnaces, respectively.

3.2.1 Ownership

We categorize firms by three basic types of ownership: central SOEs, provincial SOEs and private firms. Central SOEs are under the direct supervision of the State-owned Assets Supervision and Administration Commission (SASAC). We also define firms that have been merged into central SOEs as central state-owned. Provincial SOEs are under the direction of provincial or regional SASACs. Private firms in our sample include newly established firms and privatized SOEs, which were the product of restructuring efforts in the state sector in the late 1990s and early 2000s.

Column (1) of Table 1 provides a breakdown of ownership for our sample, which is skewed in favor of state-owned firms, at the equipment level by stage of production and by integrated facility. In each of the three stages of production, between seventy and eighty percent of machines/furnaces are state-owned. State-owned firms are also consistently the source of eighty percent of total production, with the remainder coming from private firms. Within the state sector, provincial SOEs have the largest market share. From a policy perspective, central SOEs are strategically more important and the major beneficiaries of policy choices at the national level.

3.2.2 Size

Steel firms span a wide range of sizes at both the equipment and integrated facility level. By industry convention, we measure the size of a sintering machine by its effective area; size of a blast furnace by its effective volume; and the size of basic oxygen furnace by its tonnage.

[23] We lose observations from a small number of firms and integrated facilities because of missing data. At the stage level, we have complete data on 70 firms in sintering, 71 in pig-iron making, and 68 firms in steel making.

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https://doi.org/10.1162/rest_a_00923

We define the size of an integrated facility as the total size of basic oxygen furnaces within the facility. These size measures directly reflect production capacity.

Panels A to C of Table 1 provide summary data on equipment size for each stage of production by ownership. A clear ranking emerges: On average, machines/furnaces of central state-owned facilities are the largest, followed by those of provincial state-owned and then private facilities. A typical private machine/furnace is only 60 percent of the size of a central state-owned machine/furnace. The average size of a private pig-iron furnace, for example, is 699 cubic meters compared to 1230 for a furnace of a central state-owned facility. Note also in columns (4) and (5) the wide range of equipment sizes within each ownership group. Panel D of Table 1 provides comparable information at the integrated facility level. Central SOEs operate the largest facilities, which on average are more than twice as large as those of the private facilities (301 tons versus 131 tons), and a third larger than the facilities of provincial SOEs (301 tons versus 227 tons).

In Table 2, we break down integrated facilities into size quartiles and report for each quartile the total number of facilities by ownership and their respective shares of total steel production. Almost half of the facilities in central SOEs are in the largest size quartile: they produce 14.1 percent of total steel, and make up three-quarters of the total production by central state-owned facilities. The number of facilities of provincial SOEs is fairly evenly distributed throughout the quartiles, but those in the largest size quartile play a dominant role in total steel production. In sharp contrast with the state-owned facilities, only a single private integrated facility lies in the largest size group. Most private facilities are smaller in size than the sample median. In terms of the total production of private facilities however, the integrated facilities in the third quartile are the most important, and produce 37 percent of the steel by private facilities.

3.2.3 Internal Configuration of Integrated Facilities

As part of a single integrated facility, firms will typically operate multiple pieces of equipment, e.g. sintering machines, blast furnaces or basic oxygen furnaces, in each stage of

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production. In Table 3 we report the average number of machines/furnaces and their average size for each stage of production by ownership and facility size. As before, we break down integrated facilities into size quartiles. As a general rule, the number of machines/furnaces used in each stage increases with the facility quartile. The increase however is less than proportional to the increase in the facility size, implying a four-fold increase in average machine/furnace size between the 1st and 4th quartile for integrated facility. For central state-owned facilities, the number of sintering machines and blast furnaces actually falls with facility size. For steel, they increase, but less rapidly than they do in either provincial state-owned or private facilities. This behavior gives rise to systematic differences in the number of machines/furnaces and their size in each stage of production as the size of the integrated facility increases. In particular, central state-owned facilities consistently operate the smallest number and largest machines/furnaces in each size category, followed by provincial state-owned and then private facilities. Alternatively, when private firms build larger integrated facilities, they do so using more machines/furnaces of smaller average size compared to SOEs.[24]

The Nature of Internal Configuration A firm's choice with respect to the internal configuration of their operations reflects both supply and demand side factors. In the Appendix, we sketch out an illustrative model that captures influences on the size and number of equipment a firm operates and possible tradeoffs. We abstract from decisions on total investment in production capacity, that is, we take investment in production capacity as given.

Increasing returns to scale in equipment (furnace) size provide firms clear incentives to achieve their desired production capacity using larger equipment (furnaces).[25] As they try

[24] To examine this relationship more fully, we estimate Poisson regressions of the number of equipment in each stage of an integrated facility on log facility size and log size interacted with our ownership dummies for each individual stage. We estimate related regressions for log equipment size on facility size. Results are reported in Tables A1 and A2 of the Appendix.

[25] Estimates of return to scale are reported in Section 5.3.

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Table 1: Summary Statistics of Equipment and Facility Size by Ownership

Panel A: Sintering (Machine)					
	(1)	(2)	(3)	(4)	(5)
	Number	Mean Size	Std. Dev	Min	Max
Total	343	156	127	24	853
Central	56	204	161	24	853
Provincial	203	158	127	24	550
Private	84	122	84	24	360
Panel B: Pig-Iron Making (Blast Furnace)					
	(1)	(2)	(3)	(4)	(5)
	Number	Mean Size	Std. Dev	Min	Max
Total	490	1016	926	128	5500
Central	92	1230	1046	200	4038
Provincial	249	1127	1036	128	5500
Private	149	699	460	179	2680
Panel C: Steel Making (Basic Oxygen Furnace)					
	(1)	(2)	(3)	(4)	(5)
	Number	Mean Size	Std. Dev	Min	Max
Total	342	95	62	12	300
Central	68	123	66	30	260
Provincial	209	93	63	12	300
Private	65	72	39	30	180

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Table 1: Continued: Summary Statistics of Equipment and Facility Size by Ownership

Panel D: Integrated Facility

	(1) Number	(2) Mean Size	(3) Std. Dev	(4) Min	(5) Max
Total	136	218	185	30	990
Central	26	301	212	30	840
Provincial	77	227	190	30	990
Private	33	131	96	40	540

Notes: The size of a sintering machine is measured by its effective areas in m^2; the size of a blast furnace is measured by its effective volume in m^3; the size of a basic oxygen furnace is measured by its tonnage. Facility size is measured by the total size of basic oxygen furnaces (steel making) within the facility.

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Table 2: Number and Production Share of Integrated Facilities by Size

Panel A: Size Distribution of Integrated Facilities

	(1)	(2)	(3)	(4)	(5)
	1st quartile	2nd quartile	3rd quartile	4th quartile	Total
	Number	Number	Number	Number	Number
Central	3	6	5	12	26
Provincial	16	21	18	22	77
Private	13	11	8	1	33
Total	32	38	31	35	136

Panel B: Output Share by Integrated Facilities Size

	(1)	(2)	(3)	(4)	(5)
	1st quartile	2nd quartile	3rd quartile	4th quartile	Total
	Output Share	Output Share	Output Share	Output Share	Output Share
Central	1.1%	1.5%	2.9%	14.1%	19.5%
Provincial	5.8%	11.6%	14.3%	30.9%	62.5%
Private	4.3%	4.6%	6.7%	2.4%	18.0%
Total	11.1%	17.6%	23.8%	47.5%	100.0%

Notes: Facility size is measured by the total size of basic oxygen furnaces (steel making) within the facility. The size of a basic oxygen furnace is measured by its tonnage. The size quartiles are calculated over the facility-month observations in the whole sample and are defined as follows: <90, [90,160), [160,300) and ≥ 300. Output is measured in tons of steel.

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Table 3: Internal Configuration of Integrated Facilities by Size

Panel A: Sintering (Machine)						
		(1)	(2)	(3)	(4)	(5)
Ownership	Variables	Total	1st quartile	2nd quartile	3rd quartile	4th quartile
Central	Number of Machines	1.98	1.89	2.38	2.50	1.63
	Average Size	274	104	95	222	416
Provincial	Number of Machines	2.41	1.77	2.22	2.41	2.91
	Average Size	186	117	141	225	236
Private	Number of Machines	2.12	1.71	2.31	2.09	5.00
	Average Size	129	74	147	151	360

Panel B: Pig-Iron Making (Blast Furnace)						
		(1)	(2)	(3)	(4)	(5)
Ownership	Variables	Total	1st quartile	2nd quartile	3rd quartile	4th quartile
Central	Number of Furnaces	2.32	2.48	2.28	2.13	2.38
	Average Size	1938	435	985	1902	2768
Provincial	Number of Furnaces	2.66	1.99	2.84	2.59	2.90
	Average Size	1423	633	809	1770	2145
Private	Number of Furnaces	2.82	1.85	3.29	3.56	3.00
	Average Size	707	482	614	828	2680

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Table 3: Continued: Internal Configuration of Integrated Facilities by Size

Panel C: Steel Making (Basic Oxygen Furnace)						
		(1)	(2)	(3)	(4)	(5)
Ownership	Variables	Total	1st quartile	2nd quartile	3rd quartile	4th quartile
Central	Number of Furnaces	2.44	1.37	1.83	2.26	3.08
	Average Size	127	48	87	94	180
Provincial	Number of Furnaces	2.56	1.49	2.21	3.09	3.09
	Average Size	94	46	67	81	152
Private	Number of Furnaces	1.90	1.09	2.00	2.69	3.00
	Average Size	75	54	79	84	180

Notes: Facility size is measured by the total size of basic oxygen furnaces (steel making) within the facility. The size quartiles are calculated over the facility-month observations in the whole sample and are defined as follows: <90, [90,160), [160,300) and ≥300. The size of a sintering machine is measured by its effective areas in m^2; the size of a blast furnace is measured by its effective volume in m^3; the size of a basic oxygen furnace is measured by its tonnage.

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to expand however, private firms appear to face much more severe constraints compared to SOEs. Foremost are central government regulations, which make it very difficult for private sector firms to obtain the permission required to build larger facilities. These kinds of hurdles have increased with problems of excess capacity in the industry. Firms often try to circumvent these restrictions by carrying out a series of smaller projects that use smaller equipment (furnaces).

Better human capital and higher quality raw materials are needed to take full advantage of the new technology embodied in larger equipment (furnaces). Private sector firms are generally disadvantaged vis-à-vis SOEs in both respects, thereby reducing the returns to installing equipment (furnaces) of larger size. The same is true with respect to the cost of finance, which makes it more difficult for private firms to mobilize the funds needed to make the investments associated with larger equipment (furnaces).

Demand-side considerations and profitability may also factor in, but in the opposite direction. In the face of demand shocks, it is costly for firms to shut down (start up) furnaces; moreover, these costs are increasing in the size of the equipment. This makes it much more difficult for a firm with a large furnace to adjust to demand shocks in the short run. By contrast, firms with smaller units can adjust production more efficiently by simply suspending operations in a subset of their furnaces rather than by shutting down their entire operations. In principle, this logic should apply equally to private firms and SOEs. Differences in the weight on profit maximization in the firm's objectives however may make such behavior more common in the case of private sector firms.

4 Estimating Total Factor Productivity of Integrated Facilities

This section describes a framework for estimating total factor productivity of multiple-stage production systems. Section 4.1 discusses the timeline of firms' decision. Section 4.2 presents the theoretical framework and the methodology to construct productivity for

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integrated facilities. Section 4.3 explains the details of our estimation procedure.

4.1 Description of Decision-Making

Firms make choices regarding investment and production. At the beginning of each year, a firm observes its state, which includes observable variables that affect their input access, output market, and borrowing/regulatory constraints that depend on ownership. Based on its initial state, the firm chooses its targeted level of total production to maximize current profit. This production must then be allocated among integrated facilities and machines/furnaces in each stage to minimize its total production cost. During the year, the firm carries out the production plan and generates final outputs. At the end of the year, the firm decides on investment, which depends on the current state. This decision has dynamic implications: first, larger machines/furnaces are less flexible with respect to input choice and potentially more costly to maintain/adjust, which affects the expected payoff when there is uncertainty in the input and output market; and second, larger machines/furnaces enjoy the benefits of increasing returns to scale. Moreover, the choice of investment (i.e., the size of the facility, and its internal configuration) may be limited by various constraints (e.g. tighter regulatory hurdles, access to finance, human capital, raw materials, etc) that depend on ownership.

Since we have a short panel, we leave the investigation of the full industry dynamics for future research. This paper centers on productivity differences by facility ownership related to facilities' internal configuration. Here we take advantage of the monthly frequency of our data at the facility level and focus on the monthly production of facilities. At the beginning of each month, each facility observes its stock of capital and labor and then the productivity of its individual machines/furnaces. Based on these observables, the facility decides intermediate inputs for its individual machines/furnaces. Note that the facility obtains its intermediate inputs used in a downstream stage from production in the previous stage. Following convention, we assume that intermediate input choices are monotone with respect to productivity in each corresponding stage. At the end of this month, the facility

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decides on the number of workers and maintaining/utilizing certain machines/furnaces in the next month.

4.2 A Model of Multiple-Stage Production

In each period t, an integrated facility (facility "i") engages in three major stages of production, i.e., sintering (stage "1"), pig-iron making (stage "2") and steel making (stage "3"). Along this production chain, output in each stage serves as the key material input for the subsequent downstream production stage. Each stage (plant) may involve a single or multiple machines/furnaces j. For simplicity, we omit i and t in the description of the model.

A complete production process is described as below:

$$\begin{cases} Y_{1j_1} = \min\{e^{\omega_{1j_1}} L_{1j_1}^{\alpha_1} K_{1j_1}^{\beta_1}, \gamma_1 R_{1j_1}\} e^{\epsilon_{1j_1}}, \\ Y_{2j_2} = e^{\omega_{2j_2}+\epsilon_{2j_2}} L_{2j_2}^{\alpha_2} K_{2j_2}^{\beta_2} R_{2j_2}^{\gamma_2}, \\ Y_{3j_3} = e^{\omega_{3j_3}+\epsilon_{3j_3}} L_{3j_3}^{\alpha_3} K_{3j_3}^{\beta_3} R_{3j_3}^{\gamma_3}, \end{cases} \tag{1}$$

where

$$\sum_{j_1} Y_{1j_1} = \sum_{j_2} R_{2j_2},$$
$$\sum_{j_2} Y_{2j_2} = \sum_{j_3} R_{3j_3},$$
$$Y_3 = \sum_{j_3} Y_{3j_3},$$

and R_{1j_1} represents crude iron ore fine, Y_{1j_1} and R_{2j_2} denote sinter, Y_{2j_2} and R_{3j_3} pig-iron, and Y_{3j_3} denotes the final product steel.[26] Our measure of capital K_{sj_s} is the capacity of

[26]Strictly speaking, iron ore fed into the furnace is a mixture of 75% sinter, 15% pellets and 10% lump iron ore. Since we have limited information on the latter two, we abstract from their role in the first stage and use total tonnage of the mixture in the second stage.

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the equipment j in stage s, $s = 1, 2, 3$, and L_{sj_s} is the corresponding number of employees. Productivity ω_{sj_s} is Hicks-neutral. Moreover, output from different machines/furnaces within a stage are perfect substitutes. As sintering is an agglomeration process that reshapes iron ore to the size and strength necessary for pig-iron making, this stage of production is assumed Leontief in materials.[27]

Our model reflects several important properties of production in the steel industry. First, inputs in different stages are not perfect substitutes, an assumption that is implicitly imposed in the standard firm-level production function. Second, upstream inputs, namely, labor and capital, contribute to the entire production chain through their role as intermediate material providers. Ignoring these features may result in biased estimates of input elasticity, and thus, estimates of returns to scale and TFP.

To see this more clearly, consider as a counterpart to our production function process the standard aggregate (log) production function for firm i at time t. We omit subscripts i and

Provided that the proportions are constant, this simplification produces consistent estimates except for the intercept in the second-stage production function.

[27]Substitution may exist between raw iron ore and labor (capital), mostly likely due to the quality of iron ore. However, we do not have information on the raw iron ore used in sintering. As we discuss more fully in Section 5.4, our inability to control for raw material differences likely results in a lower bound estimate of productivity of private firms in sintering relative to SOEs. In pig-iron making and steel making, taking furnace size as given, a Leontief production function in materials may better describe the production technology because materials are used in fixed proportions in the production process based on engineering designs. However, the share of material inputs in production changes with furnace size, suggesting that a Leontief production function in materials likely fails to capture the potential substitutability. We provide estimation results using Leontief production functions in Tables A3 and A4 of the Appendix.

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t for simplicity.

$$y_3 = \tilde{\omega} + \alpha\tilde{l} + \beta\tilde{k} + \tilde{\epsilon},$$

where $\tilde{l}$ is the logarithm of total labor input and equal to $\log(L_1 + L_2 + L_3)$, and $\tilde{k}$ is $\log(\tilde{K}_1 + \tilde{K}_2 + \tilde{K}_3)$, the logarithm of total capital input measured in value terms. In the case of labor, the aggregate production function implicitly assumes that the contribution of labor input to output is of the form of $(L_1 + L_2 + L_3)^{\alpha}$, which implies that what matters to production is the total amount of labor input and not the allocation of labor across production stages. Labor inputs in each stage are perfectly substitutable with firms able to move workers freely across stages at no expense of output. In contrast, our multi-stage specification allows the role of labor to differ by stage. For example, the contribution of labor is of the form of $(L_1^{\alpha_1\gamma_2\gamma_3} L_2^{\alpha_2\gamma_3} L_3^{\alpha_3})$ in the case in which each stage operates a single machine/furnace. Moreover, the elasticity coefficients are asymmetric, reflecting the sequential nature and relative importance of these inputs.

An important advantage of the above production system is that it allows intuitive calculation of facility-level return to scale and aggregation of stage productivity. First, we calculate the facility-level return to scale, defined as the ratio between the percentage change in output and the associated proportional change in inputs. Multiplying each capital and labor term in production process (1) by a positive constant a leads to new amounts of outputs

$$\begin{cases} Y_{1j_1}(a) = a^{\alpha_1+\beta_1} Y_{1j_1}, \\ Y_{2j_2}(a) = a^{\alpha_2+\beta_2} a^{(\alpha_1+\beta_1)\gamma_2} Y_{2j_2}, \\ Y_{3j_3}(a) = a^{\alpha_3+\beta_3} a^{[(\alpha_2+\beta_2)+(\alpha_1+\beta_1)\gamma_2]\gamma_3} Y_{3j_3}. \end{cases}$$

Note that $a^{\alpha_s+\beta_s}$, where $s = 1, 2, 3$, is due to the proportional changes in the current stage capital and labor. This proportional change propagates into the next stage and has a proportional effect on its output, as well. Therefore, the facility-level returns to scale (RS) is characterized by the sum of the capital and labor elasticities in each stage of production

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weighted by the material input elasticities:

$$RS = (\alpha_1 + \beta_1) \cdot \gamma_2\gamma_3 + (\alpha_2 + \beta_2) \cdot \gamma_3 + (\alpha_3 + \beta_3). \tag{2}$$

The propagation effects on the outputs in the downstream stage deserve some attention. Outputs from the upstream stage are intermediate inputs in the immediate downstream stage. In principle, the firm could change intermediate input use by different proportions in downstream furnaces. However, due to the homogeneity of the production functions, it is optimal for the firm to apply the same proportional change to each furnace.[28]

Second, we follow Domar (1961) to construct an estimate for facility-level productivity by aggregating productivity across the three stages. In particular, we define facility-level productivity as a weighted sum of stage productivity, i.e.,

$$\omega = \tilde{\omega}_1 \cdot \gamma_2\gamma_3 + \tilde{\omega}_2 \cdot \gamma_3 + \tilde{\omega}_3. \tag{3}$$

We measure stage-level productivity $\tilde{\omega}_s$ by the weighted average productivity across machines/furnaces of stage s, $s = 1, 2, 3$, using the deterministic parts of the production function as weights. Intuitively, the facility-level productivity ω reflects the sum of productivity in each stage of production weighted by its importance in the production chain using elasticities. Alternatively, we can use the value shares of pig-iron and sinter out of the total value of steel as the corresponding weights.

The facility-level productivity reflects how efficiency variations in each stage propagate into later stages. We now describe the intuition using the case in which each stage only involves a single machine/furnace. Applying the Leontief first-order condition for sintering, we proceed with the following (log) production system:

$$y_3 = \omega + \alpha_1\gamma_2\gamma_3 l_1 + \alpha_2\gamma_3 l_2 + \alpha_3 l_3 + \beta_1\gamma_2\gamma_3 k_1 + \beta_2\gamma_3 k_2 + \beta_3 k_3 + \epsilon,$$

[28] A detailed proof is available in the Appendix.

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where $\omega \equiv \omega_3 + \gamma_3\omega_2 + \gamma_2\gamma_3\omega_1$ and $\epsilon \equiv \epsilon_3 + \gamma_3\epsilon_2 + \gamma_2\gamma_3\epsilon_1$ are facility-level productivity and facility-level noise, respectively.

4.3 Estimation Approach

In this section, we develop a modified control function approach to estimate the production system of vertically-integrated steel facilities. This approach is based on Olley and Pakes (1996) and relies on a production unit's choice on intermediate inputs to control for unobserved productivity (Levinsohn and Petrin (2003)). A major advantage of our data is that it contains equipment-level information on inputs and output, which allows estimating production functions by stage-equipment and the calculation of equipment-level productivity estimates.[29]

We adapt the control function approach to allow for interdependence across stages within the facility. To this end, we allow the optimal intermediate input demand function of a machine/furnace to depend on not only its own state capital and labor, but also the amount of production required in the subsequent stages of production. For simplicity, we omit subscript i in the description of our approach. The demand functions of intermediate inputs of the three production stages $\phi_{st}(\cdot)$, $s = 1, 2, 3$, are as follows:

$$e_{1j_1t} = \phi_{1t}(k_{1j_1t}, l_{1j_1t}, \omega_{1j_1t}, k_{2t}, l_{2t}, n_{2t}, \omega_{2t}, k_{3t}, l_{3t}, n_{3t}, \omega_{3t}), \tag{4}$$

$$e_{2j_2t} = \phi_{2t}(k_{2j_2t}, l_{2j_2t}, \omega_{2j_2t}, k_{3t}, l_{3t}, n_{3t}, \omega_{3t}), \tag{5}$$

$$e_{3j_3t} = \phi_{3t}(k_{3j_3t}, l_{3j_3t}, \omega_{3j_3t}), \tag{6}$$

where k_{st},l_{st},ω_{st} are the average capital, labor and TFP of stage s, $s = 2, 3$, and n_{st} the total

[29] We abstract from firms' entry/exit decisions since they are not prominent in the data. We also do not take into account monthly entry/exit decisions on machines/furnaces, but these could be dealt with in a manner similar to Olley and Pakes (1996). Effectively, we can estimate the probability that a machine/furnace shuts down and use it as a control in our production function estimation.

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number of machines/furnaces of stage s. We use energy input to control for unobserved TFP in sintering ω_{1j_1t} and pig-iron making ω_{2j_2t}, and use scrap steel input to control for unobserved TFP in steel making ω_{3j_3t}.

Following Ackerberg et al. (2015), we assume that $\phi_{st}(\cdot)$ is strictly monotone in ω_{sj_st} conditioning on (k_{sj_st}, l_{sj_st}), and for sintering and pig-iron making, on the information of downstream stages as well. In addition, the scalar unobservability condition also holds in our setting due to the timing assumptions of firms' input choices, so we can invert the above relationships to control for the unobserved productivity. To proceed, we first invert the demand function of steel making (6), estimate the production function of this stage, and obtain estimates of average TFP $\widehat{\omega}_{3t}$. After we plug the estimated $\widehat{\omega}_{3t}$ into the intermediate input demand function for pig-iron making, the only remaining unobservable in the demand function (5) is productivity ω_{2j_2t}. We then invert the demand function (5) to obtain a control function for productivity ω_{2j_st} and estimate the stage-2 production function. Next, we plug both the estimated productivity of pig-iron making $\widehat{\omega}_{2t}$ and steel making $\widehat{\omega}_{3t}$ into the intermediate input demand function of sintering (4) and estimate the production function of sintering.

Equations (7), (8), and (9) provide the control functions for steel making, pig-iron making and sintering.

$$\omega_{3j_3t} = \phi_{3t}^{-1}(k_{3j_3t}, l_{3j_3t}, e_{3j_3t}), \tag{7}$$

$$\omega_{2jt} = \phi_{2t}^{-1}(k_{2j_2t}, l_{2j_2t}, e_{2j_2t}, k_{3t}, l_{3t}, \widehat{\omega}_{3t}), \tag{8}$$

$$\omega_{1jt} = \phi_{1t}^{-1}(k_{1j_1t}, l_{1j_1t}, e_{1j_1t}, k_{2t}, l_{2t}, \widehat{\omega}_{2t}, k_{3t}, l_{3t}, \widehat{\omega}_{3t}). \tag{9}$$

Our first-step estimating equation for each individual stage is then given by the equation below, which expresses output y as a semiparametric function of $(k_{sj_st}, l_{sj_st}, e_{sj_st}, r_{sj_st})$ and of the information of downstream stages in the case of stage 1 sintering and stage 2 pig-iron

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making.

$$y_{sj_st} = \alpha_s l_{sj_st} + \beta_s k_{sj_st} + \gamma_s r_{sj_st} + \phi_{st}^{-1}(\cdot) + \epsilon_{sj_st}.$$

As usual, we collect the deterministic terms and denote them as $\Phi_{st}(\cdot) \equiv \alpha_s l_{sj_st} + \beta_s k_{sj_st} + \gamma_s r_{sj_st} + \phi_{st}^{-1}(\cdot)$. Note that for stage $s = 1$, the same analysis follows by leaving out r_{1j_1t} due to the Leontief technology.

Ackerberg et al. (2015) argue that it may take longer to adjust capital and labor input use optimally than intermediate inputs, which include materials and energy. Since our data are on a monthly basis and include large SOEs that face significant hiring and firing costs, labor is likely to be fixed or quasi-fixed. Therefore, it is reasonable to assume that the demand for intermediate inputs depends on productivity and the predetermined capital and labor input. The advantage of using energy inputs as control variables is two-fold: first, energy input is measured in terms of standardized coal, which addresses the issue of potential bias resulting from quality differences in inputs; and second, using energy input for the control function throughout the first two stages keeps our estimation consistent. We approximate $\Phi_{st}(\cdot)$ by a high order polynomial and use OLS regression for estimation. We also include ownership dummies ($Downership$), time dummies (Dt) and province dummies ($Dprovince$) in the regression. In pig-iron making, we adjust material input r by the percentage of pure ore content to control for quality variation. Basic oxygen furnaces (steel making) differ significantly in the share of steel that goes through secondary refining. One of the goals of secondary refining is to remove impurities from the molten steel, so the intensity of secondary refining potentially reflects the quality of pig-iron used in steel making. To control for input quality in steel making, we also include in the first stage a dummy to capture whether furnaces carry out secondary refining ($Dsecond_{sj_st}$) and then the share of steel that goes through secondary refining ($second_{sj_st}$).

In the second step, we estimate the parameters $\theta \equiv (\alpha, \beta, \gamma) \in \Theta$ by GMM, which exploits

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a Markov assumption on the TFP and the timing of input choices. Θ denotes the parameter space. In particular, we assume that TFP of each equipment j in stage s follows a first-order Markov process:

$$\omega_{sj_st} = g(\omega_{sj_s,t-1}) + \xi_{sj_st},$$

which says that the current productivity shock consists of an expected term predicted by productivity at $t-1$ ($\omega_{sj_s,t-1}$) plus a deviation from the expectation, often referred to as the "innovation" component (ξ_{sj_st}). Note that ω_{sj_st} is identified up to θ from the first step after taking out measurement error and unanticipated shocks from output. We regress ω_{sj_st} on a linear function of $\omega_{sj_s,t-1}$ to obtain $g(\omega_{sj_s,t-1})$.[30] Denote $\omega_{sj_st}(\theta) \equiv \widehat{\Phi_{st}}(\cdot) - \alpha l_{sj_st} - \beta k_{sj_st} - \gamma r_{sj_st}$. For a given θ, $g(\cdot)$ can be estimated and thus ξ_{sj_st} (up to θ) is obtained. The latter is used to construct the moment conditions:

$$E[(\xi_{sj_st}(\theta) + \epsilon_{sj_st}) \begin{pmatrix} l_{sj_s,t-1} \\ l_{sj_st} \\ k_{sj_st} \\ r_{sj_s,t-1} \\ \Phi_{sj_s,t-1}(k_{sj_s,t-1}, l_{sj_s,t-1}, r_{sj_s,t-1}) \end{pmatrix}] = 0.$$

Since the capital stock is a state variable at t, it should be orthogonal to the innovation shock on productivity at t. We use current labor (l_{sj_st}) as an instrument for itself because of its dynamic feature, and also include labor at $t-1$ as an additional instrument. And we use lagged material input $r_{sj_s,t-1}$ as an instrument for r_{sj_st}. As pointed out by Gandhi et al. (2019), the use of $\xi_{sj_st} + \epsilon_{sj_st}$ rather than ξ_{sj_st} alone in the moment condition is more general. We search over the parameter space Θ to find $\hat{\alpha}$, $\hat{\beta}$ and $\hat{\gamma}$ that minimize the above moment conditions.

We use the GMM procedure to identify separately production function coefficients for

[30]The results are robust to higher order polynomials.

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each individual stage s in a backward order as described above, $s = 3, 2, 1$. As is commonly done, we also add firms' age to the production function to control for potential systematic differences in technology resulting from the learning-by-doing process.[31] In steel making, we allow the status of secondary refining ($Dsecond_{sj_s,t-1}$) and the share of secondary refining ($second_{sj_s,t-1}$) to enter the productivity evolution process since secondary refining technology may potentially impact the law of motion of productivity.

Compared with a commonly used aggregate revenue production function, our procedure has several advantages. First, our setup properly captures the characteristics of the vertically-integrated production chain. Second, the use of input and output in physical units in our estimation helps eliminate price biases, and allows us to recover true productions coefficients.[32] Third, our GMM estimates correct for any endogeneity bias due to the potential relationship between input usage and unobserved productivity. Finally, disaggregated information on inputs and output by stage of production allows us to estimate accurately a multi-stage production system.

Measurement Errors The use of input and output measured in physical units helps avoid potential biases introduced by heterogeneous prices, which could reflect for example market power, misallocation, etc. But measures in physical terms can have flaws too, and may not capture potential quality differences in output, capital vintage, raw materials, or in the facility's human capital. The number of workers that we use to measure labor abstracts from differences in workers' skill level. Similar issues arise in our use of equipment capacity as our measure for the capital stock. In Section 6, we return to these issues and provide several robustness checks for possible biases stemming from these sources.

[31]Ideally we want to use a machine/furnace's age to capture this process. Lacking this information, we use the firm's age.

[32]For a detailed discussion of the biases encountered when using sales and expenditure data, see De Loecker and Goldberg (2014).

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5 Main Results

5.1 Production Function Coefficients

Table 4 presents OLS and GMM estimates of the production functions for sintering, pig-iron making and steel making, the three major production stages along the value chain for steel. For sintering, the coefficients are only provided for labor and capital, and not for materials, reflecting the assumed Leontief technology. The elasticities are largest for materials, followed by capital and labor. Of the three stages, sintering is the most capital intensive, followed by pig-iron and steel making.

5.2 Weights for Returns to Scale and TFP Construction

In order to construct facility-level returns to scale, we need to integrate the sum of the capital and labor elasticities in each stage of production weighted by the material input elasticities. For the construction of facility-level TFP, we can use either the elasticity of material inputs in each stage or value shares to integrate estimates of stage-level TFP into an aggregate measure of TFP at facility level. In Table A5 of the Appendix, we report the two sets of weights for each stage of production. As we move downstream, the contribution of stage-level production to facility-level returns to scale and efficiency increases: The weight on sintering is 0.38 compared to weights of 0.88 and 1.0 on pig-iron making and steel production, respectively. Our two sets of weights are also fairly similar in magnitude and deliver similar estimates of TFP. The subsequent analysis is based on the TFP estimates weighted by the elasticities.

5.3 Returns to Scale

Our OLS estimates suggest increasing returns to scale in sintering (1.02) and pig-iron making (1.04) but decreasing returns to scale in steel making (0.96). In contrast, our GMM estimates imply increasing returns to scale in each stage of production, with the returns for

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Table 4: Production Functions

	(1)	(2)	(3)	(4)	(5)	(6)
	Sintering		Pig-Iron Making		Steel Making	
Variables	ols	gmm	ols	gmm	ols	gmm
l	0.212***	0.188***	0.149***	0.182***	0.0582***	0.0525***
	(0.00842)	(0.0133)	(0.00552)	(0.00190)	(0.00442)	(0.00174)
k	0.811***	0.878***	0.353***	0.449***	0.154***	0.129***
	(0.00647)	(0.000979)	(0.00553)	(0.000886)	(0.00374)	(0.00281)
m			0.534***	0.437***	0.746***	0.878***
			(0.00564)	(0.00505)	(0.00483)	(0.00295)
age	-0.00125***	-0.000516	-0.000435**	-0.000288	-0.000442***	-0.000564*
	(0.000300)	(0.00168)	(0.000176)	(0.000538)	(0.000102)	(0.000327)
Observations	6,386	6,386	8,082	8,082	8,485	8,485
R-squared	0.830		0.919		0.927	
Ownership FE	YES	YES	YES	YES	YES	YES
Province FE	YES	YES	YES	YES	YES	YES
Time FE	YES	YES	YES	YES	YES	YES
Returns to Scale	1.02	1.07	1.04	1.07	0.96	1.06
	(0.048)	(0.013)	(0.024)	(0.005)	(0.026)	(0.003)

Note: Standard errors of production function coefficients using GMM estimation and returns to scale from both OLS and GMM are computed via bootstrap of 1,000 replications clustered by facility.

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sintering (1.07) and pig-iron making (1.07) similar to those in steel making (1.06).[33]

These differences are reflected at the facility level (see equation (2) in Section 4.2), where we find increasing returns to scale of 1.14 based on the GMM estimates, and basically constant returns to scale using the OLS estimates.[34] Our OLS estimates suggest that decreasing returns to scale in the final stage of production offsets the advantages of increasing returns to scale in the first two stages. In contrast, the facility-level estimate from GMM suggests that the three stages contribute to overall increasing returns in a mutually reinforcing way. The increasing returns to scale at both the equipment and facility-level provide incentives for firms to build larger facilities and install larger machines/furnaces.

Our facility-level estimate based on the GMM procedure is larger than several recent estimates for the industry, notably, an estimate of 1.03 by Collard-Wexler and De Loecker (2015) and estimates for China of 1.01 by Brandt et al. (2017) and 1.07 by Sheng and Song (2012).[35] We cannot rule out differences in the sample of firms used in the estimation as a

[33] We replicate the estimation for steel making for a thousand bootstrapped samples, and find that the mean of the returns to scale from GMM is statistically larger than the returns to scale from the OLS. The difference between OLS and GMM for sintering and pig-iron making is not statistically significant, however both sets of estimates imply increasing returns to scale.

[34] The standard error for the estimate of the returns to scale calculated from the GMM estimates at the facility level is 0.008.

[35] Possibly underlying these differences is some combination of the estimation of an aggregate production function, and in the case of Sheng and Song (2012) and Brandt et al. (2017), estimation of a revenue production function. The latter is necessary because of the lack of firm-level price information. De Loecker and Goldberg (2014) point out that variation in both output and input prices in a revenue production function likely results in a downward bias in production function coefficients and therefore a lower returns to scale. Collard-Wexler and De Loecker (2015) construct firm-level input and output deflators, and thus effectively

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potential source of the differences with other estimates for China, but some of the difference may be related to the aggregation biases we discussed in Section 4.2. In Table A6 of the Appendix, we report the results of estimating a facility-level aggregate production function based on our equipment level input and output data. In order to obtain an estimate of the value of the total capital stock at the facility level, we value the equipment in each stage using price information for this equipment by its size. The price data we have are less than perfect, but the results from this exercise suggest decreasing returns to scale at the aggregate level. Since integrated facilities in the steel sector ran by SOEs are significantly larger than those of private sector firms, the use of aggregate data to estimate production parameters may result in a biased assessment of productivity of SOEs relative to private sector firms.[36]

5.4 Productivity Differences by Ownership

We present estimates of facility-level productivity differentials by ownership in Table 5. Estimates are obtained from simple OLS regressions of the log of facility-level TFP on ownership dummies that control for the effect of seasonality with the use of monthly dummies. In these regressions, facilities of central state-owned facilities are our omitted category. At the facility level, we do not find statistically significant differences in productivity by ownership. Column (1) shows that private integrated facilities are on average 7.4 percent more productive than the facilities in central SOEs, and are 1.1 percent more productive relative to provincial SOEs, however these differences are not statistically significant. For all of manufacturing, Hsieh and Song (2015) find a positive productivity premium for private firms of 33 percent for 2007. Our point estimate is more in line with Berkowitz et al. (2017), who report a

estimate a production function in physical terms.

[36]By comparison with the estimates in Table 5, the premium of private firms at the facility level turns negative with the use of productivity estimates based on the aggregate production function reported in Table A7 of the Appendix and in fact turns negative. Neither of these two estimates (+7.4 and -45.6) are statistically significant however.

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premium of 8.2 percent between 2003 and 2007.[37]

Our unique data allow us to examine more carefully productivity differences at the facility level by analyzing similar differences by stage of production. In columns (3), (5) and (7) of Table 5, we report estimates of productivity by ownership for each stage of production.[38] In both pig-iron making and steel-making, private facilities have a productivity advantage over central state-owned facilities of 6.1 percent and 6.2 percent, respectively. The premium of private facilities in both stages is slightly smaller in comparison with provincial state-owned facilities. In sharp contrast, the productivity ordering by ownership is reversed for sintering: Sintering machines of central state-owned facilities are 10.8 percent more productive than private facilities, and 9.3 percent more productive than provincial state-owned facilities. The lack of a clear ordering of productivity by ownership at the facility level is a product of these opposing forces.

In columns (4), (6) and (8), we report results that also control for the size of equipment. In the context of increasing returns to scale in each stage, these estimates show that productivity declines systematically with equipment size. Firms do not fully leverage the returns offered by equipment of larger size. Since the equipment used by SOEs is larger in size than that by

[37]Differences in these estimates may come from several sources: First, estimation of a value-added versus gross-output production function. Although both value-added and gross-output based TFP indices provide a measure of technological change, the two will not necessarily be the same (Balk (2009)). Second, differences in assumptions relating to the underlying production technology, e.g., Cobb-Douglas versus CES versus translog, may result in differences in estimated TFP and our productivity ranking. And third, some estimates may only reflect within-sector variation, while others capture both within and between sector differences in TFP.

[38]Estimates at the equipment level are also obtained from OLS regressions with the use of monthly dummies. In these regressions, equipment of central state-owned facilities are our omitted category.

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private firms, inclusion of size dampens the premium of private firms in pig-iron and steel making, and in the case of sintering, highlights an even larger gap private firms (and for that matter, provincial SOEs) face vis-à-vis central SOEs.

What might help to explain the reversal in the productivity by ownership in the case of sintering? A simple comparison of labor and capital productivity in sintering suggests only modest differences between private firms and central SOEs in output per unit of capacity, however, labor productivity in private firms is only one-half of that in central SOEs (see Table A8 of the Appendix). This implies that private firms use two times as much labor per unit of output than do central SOEs. Two related factors are important here. First, despite the use of similar technology in the major process of sintering, industry reports suggest firms differ in the choice of equipment in auxiliary processes, e.g. mixture of raw materials, with SOEs using more automated processes by comparison to the labor-intensive methods adopted by small and medium-sized private firms (Wang and Lin (2014), pp.47-50). Second, there are differences by ownership in access to high quality iron ore, which matters for equipment choice for the sub-processes, labor use and processing time. Automated equipment is more demanding in terms of the quality and uniformity of the raw materials used. Underlying this is access to imports.

China is highly dependent on imported iron ore. Over the three-year period between 2009 and 2011, imports were the source of 70 percent of the iron ore used by the sector (Tao (2019)). The quality of imported iron ore is also higher than the ore mined domestically, as reflected, for example, in ore's silica content, which lowers the quality of the sinter and adversely affects the production process.[39] For domestic iron ore, the silica content ranges from 6.5 to 12 percent. By contrast, imported iron ore is more homogeneous in pure ore content and contains only 4 percent silica.[40] Significant differences in access to imported iron ore exist between SOEs and private firms. Central here is changes that were made in

[39]See Gao (2006) for more details.

[40]The information on iron ore fines is based on data in Yu (2004).

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Table 5: Productivity Differences by Ownership and Size

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Facility	Facility	Sintering	Sintering	Pig-Iron Making	Pig-Iron Making	Steel Making	Steel Making
Variables	logtfp	logtfp	logtfp	logtfp	logtfp	logtfp	logtfp	logtfp
Private	0.0743	0.0382	-0.108	-0.144*	0.0612*	0.0429	0.0615***	0.0316
	(0.0616)	(0.0755)	(0.0793)	(0.0789)	(0.0352)	(0.0378)	(0.0237)	(0.0241)
Provincial	0.0633	0.0490	-0.0930	-0.115**	0.0222	0.0158	0.0155	-0.00630
	(0.0537)	(0.0581)	(0.0645)	(0.0566)	(0.0309)	(0.0310)	(0.0156)	(0.0158)
logsize		-0.0479		-0.0903**		-0.0338***		-0.0529***
		(0.0338)		(0.0405)		(0.0131)		(0.0107)
Constant	-0.113**	0.141	0.0342	0.471***	-0.0842***	0.146	-0.0420***	0.204***
	(0.0447)	(0.194)	(0.0542)	(0.176)	(0.0319)	(0.100)	(0.0140)	(0.0516)
Observations	3,440	3,440	8,728	8,728	11,836	11,836	8,510	8,510
R-squared	0.022	0.036	0.015	0.043	0.020	0.033	0.048	0.151
Time FE	YES	YES	YES	YES	YES	YES	YES	YES

Notes: Central state-owned facilities and their machines/furnaces are the omitted group. Private and provincial indicate ownership dummies. The size of a sintering machine is measured by its effective areas in m^2; the size of a blast furnace is measured by its effective volume in m^3; the size of a basic oxygen furnace is measured by its tonnage. Facility size is measured by the total size of basic oxygen furnaces (steel making) within the facility. Standard errors are computed via bootstrap of 1,000 replications clustered by facility.

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the import licensing system for iron ore in 2005 that restricted the right to import directly from foreign countries to larger privileged firms (Tao (2019) and in der Heiden (2011)). As a result, the number of firms importing iron ore fell sharply from over 500 to 112, of which 70 were steel makers (Zhang (2010)). Small and medium size firms now needed to procure imported iron ore through an agency system that required them to pay an additional 3-5 percent (in der Heiden (2011)). State-owned steel firms also resold some of the iron ore they imported at a premium. Conservatively, private steel firms used two-thirds more domestic iron ore than did SOEs: 33.3 percent versus 20 percent. Data for 2009 and 2010 indicate that rich iron ore fines - a measure of quality of iron ore used in sintering-made up 60.1 percent and 62.8 percent of the total iron ore processed in central SOEs in these two respective years, compared to 47.5 and 46.2 percent in private firms.[41] Access to less uniform and lower quality iron ore have influenced equipment choice for sintering, and necessitated additional processing to produce sinter of the required quality level for blast furnaces (Wang and Lin (2014), pp.47-50).

6 Discussion

This section examines how measurement errors in capital and output might affect our main analysis.

6.1 Measurement Error in Capital

The use of production capacity as our measure of firm capital has its advantages, but may still not fully capture differences in capital intensity between firms.[42] For example,

[41]Calculations are based on firm-level data collected by the Chinese Iron and Steel Association on an annual basis.

[42]One shortcoming of capital stock measures in value terms is that they include investments in pollution abatement equipment, which are not separately identified in the data. While these investments are good for the environment, they do not likely augment productivity. Firms that invest more in pollution control, all else equal, will likely have lower TFP. The

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investment costs per unit of capacity, which we assume are constant, might increase with equipment size.[43] The potential bias results from two sources. First, the positive correlation between capacity and unit investment cost leads to an upward bias in capital coefficients. Second, estimated productivity contains the unit price of capacity. Other things equal, the overestimate of the capital stock in private facilities would lead to a downward bias in the productivity differentials that we found in pig-iron and steel making.

To see this more clearly, we express production as a function of price-adjusted capital k^*, where k^* is the product of capacity k, our capital measure in the baseline estimation, and the unit capacity price, p.

$$y_i = \alpha l_i + \beta k_i^* + \gamma r_i + \omega_i + \epsilon_i = \alpha l_i + \beta k_i + \gamma r_i + \beta p_i + \omega_i + \epsilon_i \tag{10}$$

In our baseline model, we treat unit capacity price p as measurement error, so our estimated productivity is equal to $\hat{\beta} p_i + \hat{\omega}_i$. Since unit capacity price p is positively correlated with capacity k, this leads to a potential upward bias in the estimated parameter on capital β. Our estimates of productivity ownership differentials are also likely to be biased because our measure of productivity ($\hat{\beta} p_i + \hat{\omega}_i$) includes the unobserved unit capacity price. Consider the estimated productivity differential between private and central state-owned facilities, i.e., $\hat{\beta}(p_i^{private} - p_i^{central}) + (\hat{\omega}_i^{private} - \hat{\omega}_i^{central})$. The first term reflects capacity price differences, and the second measures the true difference in productivity. As private facilities systematically operate smaller equipment than central state-owned facilities, the unit capacity price of private machines/furnaces is generally lower. Consequently, the first term of the productivity differential is negative, which gives rise to a downward bias in the estimated productivity

use of capital measures in physical (capacity) terms is not susceptible to these biases.

[43] We extract the information on investment costs of steel plants by size from an internal report prepared by the Chinese Metallurgy Planning Institute in August 2016 per the authors' request.

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premium of private firms at the equipment level compared to central state-owned facilities. We use the price information on investment of basic oxygen furnaces (steel making) to adjust capital in this stage of production, and re-estimate the production function for steel making using this adjusted capital measure.[44] The estimated coefficients are reported in Table A9 of the Appendix. Compared to the baseline estimation, using the adjusted capital generates a lower coefficient for capital, as predicted. We report the corresponding productivity differentials in Table 6. The productivity premium of private furnaces over central state-owned furnaces rises slightly from 6.15 percent to 6.41 percent when we base our estimates on the price-adjusted capital.

Independent of furnace size, systematic differences may also exist in the costs per unit of capacity between private and state-owned facilities. In general, we expect private firms to be more cost sensitive, and for them to be successful in finding ways to build furnaces of any size at lower cost, and thus enjoy lower per unit cost of capacity relative to SOEs. This source of measurement error would further underestimate productivity premiums of private facilities. Additional information on capacity cost by ownership is needed to estimate the magnitude of this bias.

6.2 Measurement Error in Output

In our data, output is measured in physical units, obscuring output quality differences between facilities. In principle, this could bias our productivity comparisons.[45] Let y^* measure quality-adjusted output, defined as a function of observed output y and X, a vector of output quality measures. f is a general production function and is stage-specific but time-invariant. Therefore, we have $y_i^*(y_i, X_i) = f(l_i, k_i, r_i) + \omega_i + \epsilon_i$, where $y_i^* = y_i + \delta(X_i)$. Combining these two equations, we obtain our baseline production function.

[44] We did the same exercise for pig-iron making and obtained similar results as steel making.

[45] Atkin et al. (2019) also point out that importance of measuring both quantity and quality in calculating firm productivity. In their study of rug-making firms in Egypt, they develop tailored surveys to examine the tradeoff between physical productivity and quality.

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$$y_i = f(l_i, k_i, r_i) + (\omega_i - \delta(X_i)) + \epsilon_i \tag{11}$$

This makes explicit that estimated productivity $\omega_i - \hat{\delta}(X_i)$ also incorporates output quality.

Table 7 reports output quality comparisons across ownership. Grade stability rates of sinter capture the shares of sinter with the percentage of iron contents that conforms to the output quality standards of the steel industry in China. We use shares of premium iron to measure the quality of pig-iron. Our measure of steel quality is the share of secondary steel making. Typically, secondary refining serves two main purposes: first, this process can compensate for lower quality inputs; and second, it allows the steelmaker to change the properties of the steel in ways often associated with the production of higher grade steel products.[46] Table 7 shows that on average, private firms produce lower quality sinter and steel but higher shares of premium grade pig-iron compared to SOEs.

To see how differences in output quality affect productivity differentials by ownership, we re-estimate the facility- and stage-level productivity differentials by adding as controls the quality measure of each output. Table 8 shows that the point estimates and levels of significance for the productivity premium of private facilities relative to either central state-owned facilities or provincial state-owned facilities remain more or less the same at both facility and stage level. In short, our findings are robust when we allow for output quality differences.

7 Conclusion

This paper is one of the first to study the underlying sources of productivity differences by firms' ownership structure through the lens of firms' internal configuration. The new data set that we construct provides equipment-level information on inputs and output in physical

[46]See detailed description about the secondary steel refining at http://www.jfe-21st-cf.or.jp/chapter_2/2i_1.html

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Table 6: Ownership Premium of Productivity in Steel Making: Robustness Check

	(1)	(2)
	Non-Adjusted	Price-Adjusted
Variables	logtfp	logtfp
Private	0.0615***	0.0641***
	(0.0237)	(0.0240)
Provincial	0.0155	0.0147
	(0.0156)	(0.0157)
Constant	-0.0420***	-0.0413***
	(0.0140)	(0.0140)
Observations	8,510	8,510
R-squared	0.048	0.052
Time FE	YES	YES

Notes: Furnaces of central state-owned facilities are the omitted group. Provincial and private are ownership dummies. Standard errors are computed via bootstrap of 1,000 replications clustered by facility.

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https://doi.org/10.1162/rest_a_00923

Table 7: Output Quality Differences by Ownership

	(1)	(2)	(3)
	Sintering	Pig-Iron Making	Steel Making
Variables	Grade Stability	Premium Grade	Secondary
Private	-10.56**	1.354	-39.54***
	(4.243)	(3.935)	(7.873)
Provincial	-2.481	-5.717	-26.77***
	(1.929)	(3.689)	(6.698)
Constant	90.79***	65.92***	56.25***
	(1.716)	(3.365)	(6.113)
Observations	8,728	11,836	8,510
R-squared	0.027	0.018	0.093
Time FE	YES	YES	YES

Notes: All quality measures are in percentage points. Secondary denotes the share of steel that goes through secondary steel refining and provides an important piece of evidence on the quality of steel. Standard errors are clustered by machines/furnaces.

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https://doi.org/10.1162/rest_a_00923

Table 8: Quality-Adjusted Ownership Premium of Productivity

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Facility	Facility	Sintering	Sintering	Pig-iron Making	Pig-iron Making	Steel Making	Steel Making
Variables	logtfp	logtfp	logtfp	logtfp	logtfp	logtfp	logtfp	logtfp
Private	0.0847	0.0530	-0.102	-0.137*	0.0610*	0.0406	0.0432*	0.0304
	(0.0689)	(0.0747)	(0.0761)	(0.0788)	(0.0348)	(0.0369)	(0.0259)	(0.0251)
Provincial	0.0724	0.0652	-0.0915	-0.114**	0.0229	0.0174	0.00313	-0.00710
	(0.0529)	(0.0570)	(0.0650)	(0.0572)	(0.0303)	(0.0293)	(0.0136)	(0.0156)
logsize		-0.0687**		-0.0906**		-0.0371***		-0.0512***
		(0.0326)		(0.0406)		(0.0139)		(0.0113)
Constant	-0.0478	0.257	-0.0194	0.414*	-0.0925**	0.143	-0.0160	0.199***
	(0.126)	(0.217)	(0.160)	(0.213)	(0.0426)	(0.0986)	(0.0167)	(0.0522)
Observations	3,440	3,440	8,728	8,728	11,836	11,836	8,510	8,510
R-squared	0.027	0.049	0.016	0.044	0.020	0.035	0.078	0.151
Sinter quality	YES	YES	YES	YES	NO	NO	NO	NO
Pig-iron quality	YES	YES	NO	NO	YES	YES	NO	NO
Steel quality	YES	YES	NO	NO	NO	NO	YES	YES
Time FE	YES	YES	YES	YES	YES	YES	YES	YES

Notes: The quality measures of sinter, pig-iron and steel are the stability rates of sinter, shares of premium pig-iron, and shares of secondary steel making, respectively. Central state-owned facilities are the omitted group. Provincial and private are ownership dummies. Standard errors are computed via bootstrap of 1,000 replications clustered by facility.

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units for each stage in the value chain of vertically integrated facilities. In this kind of industry, the use of aggregate data may result in the estimation of biased production parameters and measures of productivity at the firm level; it may also miss important differences in the organization of production and productivity throughout the value chain.

In the context of increasing returns to scale at both the stage and facility level, statistically significant differences in productivity by ownership do not emerge between steel facilities. This conceals however important differences upstream and downstream in the value chain: Private firms outperform downstream in both pig-iron and steel making but lag significantly in the case of sintering. Constrained access to higher quality raw materials and use of less automated sintering equipment are likely candidates for their negative premium.

Our work suggests a natural direction for future research. We document significant differences by ownership in both facility size and the size of the equipment used throughout the value chain. Increasing returns to scale provide clear incentives to use larger machines and furnaces in larger facility. A variety of constraints facing firms may limit their ability to do so however. But as discussed in the end of Section 3.2.3, there are also advantages to having a portfolio of equipment with smaller average size. In order to examine these trade-offs more carefully, we need to build and estimate a structural dynamic model that looks at the role of both demand and supply side considerations in the firm's choices. This entails incorporating into a dynamic model of investment the various constraints that we identified facing firms of different ownership type. We also need to model the demand side, fluctuations in which likely shape firms' decisions on internal configuration. Access to several more years of firm level data will facilitate model identification by providing data that spans both booms and busts in China's steel market.[47]

[47] A longer panel will also make it possible to analyze the effect of key policies designed to support the steel industry.

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