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新技術が生産性に与える影響—日本の製鉄業における操業改善と生産配分—

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【要旨】

本稿では、新技術が生産性に与える影響を生産性変動の要因分解を用いて分析した。生産性の上昇を、 (1)操業改善効果：改良技術も含めた工場単位での操業改善の効果、(2)技術間の再分配効果：旧技術から新技術へ生産の再分配が行われる効果、(3)参入効果：設備の新規設立や新規参入による生産の再分配効果、(4)技術内の再分配効果：各技術内で生産の配分が変化する効果、の4要素に分解する手法を採用した。その結果、新技術の急速な操業改善と参入も含めた技術間の再分配の2つの要因が生産性上昇に同程度貢献しており、両方が等しく重要であったことを示した。また、全体的な配分の効率性は向上したが、技術内の配分効率性は低下していることもわかった。この結果により、転炉技術内の配分効率を犠牲にしつつも、急速に操業技術の進歩する転炉の普及に伴い、生産性が上昇したことが示された。

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The Effects of New Technology on Productivity: Technological Improvement and Reallocation Efficiency in the Japanese Steelmaking Industry*

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February 13, 2022

Abstract

This paper analyzes the effect of new technology for steel refining – the basic oxygen furnace (BOF) – on productivity growth using the productivity decomposition method. I employ a technique that decomposes productivity growth into four factors: operational improvement, within- and between-technology reallocation, and entry-exit effects. I demonstrate that the following two factors were equally important: (i) the rapid operational progress of new technology and (ii) between-technology reallocation both among existing furnaces and through entries (new construction). I also find that although the overall allocation efficiency improved, the within-BOF allocation efficiency declined. The results suggest that productivity growth followed the spread of BOF with rapid technological advancement while sacrificing allocative efficiency within the BOF furnaces.

Keywords: Productivity, Productivity decomposition, Between-technology reallocation, Technology, Steel industry

JEL Codes: D24, L61, O14, O31, O33

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1 Introduction

New technology is viewed as one of the major sources of productivity growth. However, some technologies are new but inefficient, and some technologies are efficient but spread slowly. How and why does an industry's productivity grow when a promising technology spreads rapidly? Does switching to a new technology immediately increase productivity, is it more important to improve the new technology itself, or both?

In this paper, I analyze the productivity effect of a new refining technology – the basic oxygen furnace (henceforth BOF) – on the Japanese steel industry from the 1950s to the 1960s using a productivity decomposition approach. In the productivity decomposition, I decompose the productivity growth into the following four effects: (i) the effect of operational improvements including the development of various improved technologies (operational improvement effect), (ii) the effect of production reallocation from the old technology – the open-hearth furnace (henceforth, OHF) – to the new technology, BOF (between-technology reallocation effect), (iii) the effect of production reallocation from less productive to more productive furnaces within the same technology (within-technology reallocation effect), and (iv) the reallocation effect caused by entry and exit through the construction of new BOFs / abatement of old OHFs (entry-exit effect).

The Japanese steel industry and the BOF technology are a suitable setting for analyzing the relationship between new technology and productivity growth for three reasons. First, the Japanese steel industry achieved rapid growth from the late 1950s to the early 1970s, with a tenfold increase in crude steel production (1957 to 1973) and a sixteenfold increase in steel exports (1957 to 1969). It is often said that BOF technology made the steel industry grow by leaps and bounds. For example, Hogan (1971) said that BOF technology is "unquestionably one of the greatest technological breakthroughs in the steel industry during the twentieth century." Japan was the third country in the world to introduce the BOF in 1957, the use of the BOF rapidly increased, and the share of the BOF in crude steel production reached approximately 80% in the 1970s[1].

In this period, the Japanese government implemented policies to promote the spread of the BOF, and Japanese steelmakers sought to improve BOF technology. The government coordinated the use of a BOF license granted by an Austrian company to be used jointly by Japanese steelmakers instead of being employed by only one firm. The government also implemented other policies, such as tax incentives, that favored the introduction of the BOF and related new technologies. When the BOF was first introduced in Japan, there were many operational challenges, but Japanese steel manufacturers enhanced BOF performance by developing improved technologies. This is thought to have promoted the spread of BOFs and increased productivity. Based on the results of the productivity decomposition analysis, I consider the effect of government policies and firm relationships on productivity growth.

I estimated a production function that considers technology heterogeneity, and by using the estimated productivity, I decomposed the productivity change into the factors mentioned above. The following results were obtained. First, when the BOF was first introduced, its productivity was comparable to that of the OHF. It was unstable and presented considerable variance, but it became more stable and productive over time.

The primary factor that induced productivity growth was operational improvements to the BOF that accounted for more than 60% of the total. The secondary factor is the reallocation of production from the old to the new technology through both between-reallocation and entry-exit effects, each contributing slightly more than a 25% share, for a total of slightly more than 50 percent. On the other hand, the allocative efficiency within the BOF technology deteriorated by nearly 40%. The results suggest that the government policies that supported BOF adoption and knowledge sharing among firms promoted BOF introduction at the expense of within-allocation efficiency. This allowed all firms to enjoy significant operational improvements.

This study contributes to two streams of literature. The first consists of papers identi-

[1]Meyer and Herregat (1974)

fying the source of productivity growth. In particular, this study is related to papers that focus on the role of technology. Specifically, Collard-Wexler and De Loecker (2015) study the effect of new technology on the U.S. steel industry's productivity growth at the plant level using decomposition analysis, which considers technology heterogeneity. I apply their production function estimation and decomposition method to study the Japanese steel industry's productivity growth at the facility level. Collard-Wexler and De Loecker (2015)) examines a situation in which new technology emerged and technologies competed. In contrast, this paper investigates a case in which new technology emerged and replaced nearly all of the old technology and does so at a more detailed unit level than their work.

The second stream of literature analyzes the Japanese steelmaking industry's growth factors from the 1950s to the 1960s. In this period, the Japanese steelmaking industry grew dramatically. Thus, many papers study it both quantitatively and descriptively. Nakamura and Ohashi (2012a, b) focus on the two major improved technologies for BOF and the intra-plant BOF diffusion pattern. I conduct a unified analysis of both the reallocation effect and the operational improvement effect that considers entry and exit.

The remainder of the paper is organized as follows. Section 2 outlines the Japanese steel industry in the 1950s and 1960s, a period of high growth, and discusses the relationship between the BOF and the steel industry's evolution. In Section 3, I explain this study's perspective with respect to previous studies that analyzed the factors of productivity change and prior studies on the Japanese steel industry during the same period. Section 4 introduces the data sources used and presents an overview of their characteristics. The model and estimation results of the production function are explained in Section 5. In Section 6, I decompose the productivity growth factors and discuss the results. Section 7 offers concluding remarks.

2 Industry overview: Japanese steel industry during the 1950s-1960s

This section describes the Japanese steel industry from the 1950s to the first half of the 1970s[2] regarding how the new technology made the steel industry grow rapidly. First, I briefly explain the Japanese steel industry's situation at that time and the features of the new technology, BOF.[3] Next, I express the possible factors contributing to the steel industry's development and productivity growth from the BOF.

The Japanese steel industry experienced rapid growth in quantity and quality from the 1950s to the first half of the 1970s. As shown in Figure 1, crude steel production, approximately 13 million tons in 1957 when the BOF was introduced in Japan, grew nearly tenfold to over 100 million tons in 1973. Steel exports also increased significantly from 1 million tons in 1957 to 16 million tons in 1969, and Japan became the world's largest steel exporter.[4] Furthermore, while the Japanese steel industry in the 1950s imported much technology from abroad, it became an exporter of steelmaking technology from the late 1960s to the 1970s. The foundation for Japan to remain the world's largest steel exporter until 2005 was in place in this period.[5]

It is said that the introduction of the BOF supported the dramatic growth of Japan. The BOF is a type of facility used in the steel refining process. In the refining process, crude steel – the intermediate product of steel products – is made from pig iron and scrap. In this process, impurities are removed, and metallic elements are added to adjust the composition to meet

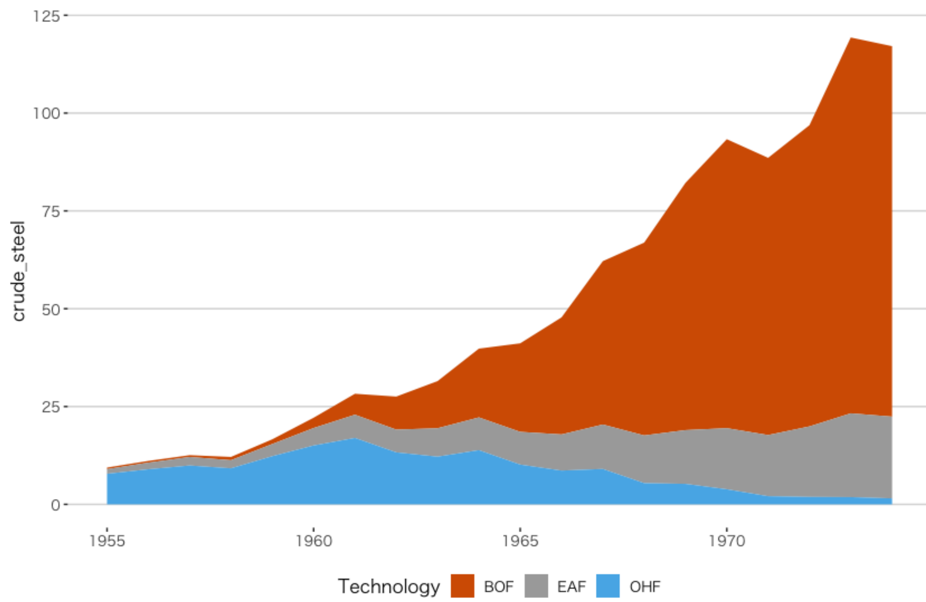
[2]This period is called "the high economic growth period" in Japan. Not only the steelmaking industry but also all Japanese industries grew dramatically.

[3]This section is mainly based on three reference documents: the "History of Oxygen Steelmaking Process in Japan" by Iron and of Japan (1982) describes the history of the BOF's introduction, improvement, and diffusion, Nakamura (2007) describes the Japanese steelmaking industry during the BOF's introduction and diffusion process from a technological history perspective; and Lynn (1982), investigates the BOF's introduction process in Japan and the United States using interviews and a survey of the historical literature.

[4]Data source: "Yearbook of Iron and Steel Statistics." (Japan Iron and Steel Federation, 1955-1968b). The export value also increased from 220 million yen to 2.30 billion yen.

[5]Data source: The World Steel Association homepage (https://www.worldsteel.org/)

Figure 1: Crude steel production in Japan (by technology)



* Data source: "Yearbook of Iron and Steel Statistics." (Japan Iron and Steel Federation, 1955-1968b).

* Crude steel production on the vertical axis is in millions of tons. See footnote 8 for why the electric arc furnace (EAF) are not included in the analysis.

the various requirements of final products.[6] The introduction of the BOF into the refining process improved productivity in four aspects, and they contributed to the development of the steel industry.

First, the BOF had advantages over the older OHF[7] in refining time and the amounts of inputs required for operation. A BOF furnace can refine steel in one-fourth to one-fifth time than an OHF furnace. As a result, a BOF can produce more crude steel with fewer furnaces than an OHF. Additionally, labor and fuel costs per unit of crude steel are lower than the OHF. Steelmaking firms reallocated production from the OHF to the BOF, which can be regarded as a productivity growth factor.[8]

[6]The rolling process is the process of making variously shaped finished products from crude steel. A steelwork is a collection of plants that conduct a series of manufacturing processes, from the iron-making process to the rolling process. A firm consists of one or more steelworks. In summary, the steelworks is the largest entity in the firm that consists of a series of manufacturing processes, and the refining process is a one of the manufacturing process. A BOF is a type of equipment/technology used in the refining process, and the refining process consists of several BOFs.

[7]In the OHF, combustion gas heated by a burner refines scraps and other iron sources.

[8] A technology called an electric arc furnace (EAF) that uses electricity to refine steel scrap and produce crude steel also exists. In contrast to BOF and OHF, which are suitable for mass production, EAF is suitable

Furthermore, it is also presumed that a policy by the Ministry of International Trade and Industry (MITI) was a factor in facilitating the reallocation of production to new technology. In the middle of the 1950s, Yawata Steel and Nihon Ko-Kan (hereafter, NKK) negotiated with foreign companies and competed to be the first to introduce BOF technology in Japan. However, MITI intervened and assigned NKK to be the only contractor. Other steel companies were granted sublicenses by paying a license fee in proportion to their crude steel production. The Japanese government did this to prevent license fees from rising due to competition. The Japanese government was concerned that monopolization of the technology by a particular firm would inhibit competition. The license fee per ton of crude steel production paid by Japanese firms was far lower than that paid in other countries. According to Lynn (1982), Japanese firms paid a license fee of 0.36 cents per ton of crude steel production, while American firms paid 15 to 25 cents per ton. As a result, the BOF introduction was not limited to a specific firm but was promoted throughout the steel industry. Additionally, the Japanese government implemented various other policies, such as tax incentives for depreciation and tariff exemptions to import equipment for BOF operation.

The third factor that may have contributed to the increase in productivity is that steelmaking firms made considerable effort to improve BOF operation. After introducing the BOF, various improvement technologies for the BOF were invented mainly by the two pioneering companies Yawata Steel and NKK. Some of the improved technologies developed in Japan were exported overseas and became world standards.[9] According to Nakamura (2007), the BOF was just one of the promising technologies at the introduction stage, and its usefulness was confirmed after the invention of technical improvements. Efforts by Japanese steel firms to improve BOF technology likely increased the whole industry's productivity.

The fourth factor is that each steelmaking company introduced the BOF not only in existing steelworks but also in newly constructed works. With the invention of improved

for the small-lot production of a wide variety of products. Additionally, the usefulness of EAF technology increased after the period of analysis, so I excluded it from this study.

[9]One of the most prominent improved technologies is the OG system, which ultimately would be used in sixty percent of the world's BOFs.

technologies, firms could increase the size of their furnaces. After the introduction of the BOF in Japan, large furnaces were built in newly constructed steelworks. This may have played a role in increasing production and productivity. In these new steelworks, steelmaking firms would have utilized the experience and up-to-date knowledge gained from operating a BOF in existing steelworks and introduced many improved technologies.

In summary, the following three factors can be considered to have affected the increase in productivity: 1) the effects of the shift in production from the old OHF technology to the new BOF technology (between-technology reallocation effect), 2) the effect of the construction of new BOFs (entry effect), and 3) the effect of operational improvements including various improvement technologies (operational improvement effect). In the following analysis, I focus on which factors account for larger shares of productivity growth and their magnitude relative to the old technology.

3 Related Literature

This section describes two strands of literature to which this paper contributes. The first examines productivity growth determinants, particularly focusing on new technology and production processes (see, e.g., Oster, 1982; Van Biesebroeck, 2003; Collard-Wexler and De Loecker, 2015).[10]

The study most closely related to this paper in this strand of literature is Collard-Wexler and De Loecker (2015, hereafter CWDL). CWDL analyze the impact of new technology on productivity using plant-level data on the U.S. steel industry between 1963 and 2002. CWDL focus on the diffusion of new technology – minimill (EAF) – and analyze the sources

[10] Various productivity determinants are explored in the literature. See Syverson (2011) for a comprehensive survey.

of industrial productivity growth via a decomposition method.[11] [12] CWDL conduct within- and between-technology decomposition and a dynamic decomposition that considers entry and exit. First, they find that one-third of the increase in productivity was due to production reallocation to new technology. CWDL show that between-technology reallocation and new technology aggregate productivity growth accounts for almost half of the industry's productivity growth. Second, CWDL reveals that the old technology caught up with the new technology to some extent. Reallocation from inefficient producers to more efficient producers within the old technology resulted from increased competition with new technology plants. As a result, old technology productivity grew faster than new technology productivity.

The second strand of literature to which this study contributes consists of papers studying the Japanese steel industry's growth in the period from the 1950s to the 1970s. The period from 1955 to 1973 is called "the high economic growth period" in Japan. Because the Japanese steel industry grew dramatically and became a globally important player (as mentioned in the industry section), numerous studies exist, both descriptive (see, e.g., Lynn, 1981, 1982; Yonekura, 1994; Nakamura, 2007; Lee and Ki, 2017) and quantitative (see, e.g., Ohashi, 2005; Nakamura and Ohashi, 2008, 2012a,b; Okazaki and Korenaga, 2015). Among the descriptive papers, Lynn (1982) suggested the role of government, and Nakamura (2007) investigates various aspects of technological history.

Among the quantitative analyses, Nakamura and Ohashi (2012a,b) study the role of BOFs and their introduction. Both papers use the same plant-level data. Nakamura and Ohashi (2012a) examine the impact on the productivity of two improved technologies in-

[11]The use of EAFs became widespread in the 1970s and 1980s. Since an EAF consumes a large amount of electricity and steel scrap, a low cost of electricity and an abundance of steel scrap are essential factors for its spread. In particular, it was used in the United States, where these factors were present. Even now, EAFs account for more than 70% of crude steel production in the United States. EAFs did not become widespread in Japan due to high electricity costs because Japan depends on imported resources such as coal for power generation. At present, the share of EAFs in Japan's crude steel production is less than 20% (data source: The World Steel Association, https://www.worldsteel.org).

[12]CWDL treat vertically integrated steelworks as the old technology. Vertically integrated steelworks have blast furnaces, BOFs or OHFs, and rolling facilities. This technology is not obsolete and accounts for over 70% of the world's crude steel production, although CWDL call vertically integrated technology "old".

vented by Japanese companies after the introduction of the BOF. Their paper reports that these two improved technologies explained 30% of the productivity increase.[13] Nakamura and Ohashi (2012b) investigate the intra- and inter-plant diffusion patterns and productivity growth.[14] They find that intra-plant diffusion accounts for half of the increase in productivity throughout the period. Moreover, large plants adopted the BOF earlier than small plants, but relatively small plants' intra-plant diffusion was faster than that of larger plants. Additionally, they show that in the early stage of introduction, the intra-plant diffusion effect was significant. However, the inter-plant diffusion effect became more extensive in the later stage.

This paper provides a unified quantitative analysis of the impact of new technology (BOF) on productivity by decomposing productivity into (i) the operational improvement effect, (ii) between-technology reallocation effect, (iii) within-technology reallocation effect, and (iv) entry-exit effect, based on the method of CWDL This paper is the first study to decompose productivity into factors (i) to (iv) in the literature on productivity growth in the Japanese steel industry during the 1950s and 1960s. While Nakamura and Ohashi (2012a,b) focus on specific points, this paper comprehensively analyzes productivity growth, considering within- and between-technology and dynamic effects in terms of entry and exit. Collard-Wexler and De Loecker (2015) analyze the situation where a new technology emerged and came to compete with the old technology. In contrast, this study is unique in analyzing the phase of technology replacement.

4 Data Source and Definition of Variables

The primary data source is the *"Reference Material on Steel Making"* (Japan Iron and Steel Federation, 1957-1968), and output and all inputs other than capital data are obtained; data for capital inputs are obtained from each firm's annual securities report. The following values

[13]They focus on the oxygen converter gas recovery system and the multi-hole lance.

[14]In their decomposition, intra- and inter-plant diffusion contain the operational improvement effect and entry-exit effect because their interest is in intra-plant diffusion.

are used as the output, inputs, and intermediate inputs for the control functions.

1. Output: Crude steel production
2. Labor input: The total working hours in the crude steel production process
3. Capital input: The capacity of a furnace [15][16]
4. Intermediate inputs: Pig iron and steel/iron scrap [17]
5. Energy inputs: Electricity and heavy oil

Value-added output is calculated as the amount of crude steel measured by price less intermediate and energy inputs' amounts in prices.

The price data sources are as follows. The first is the *"Yearbook of Iron and Steel Statistics"*, which contains the prices of crude steel, pig iron, and scrap. The second is the *"Yearbook of Petroleum Statistics"*, which includes heavy oil prices.[18] The last is the *"Annual Report on Energy"* form, from which the electricity price is acquired. Price data are deflated by the wholesale price index.

This paper's analysis is at the furnace level, although the *"Reference Material on Steel Making"* reports data at the steelworks-technology level rather than the furnace level. Thus, I need to assign data obtained from this data source to the furnace level. To that end, I allocate crude steel production, labor, energy, and intermediate inputs in proportion to a furnace's capacity. Additionally, since the labor data are observed as the number of employees and not reported based on furnace technology type, they are assigned in advance to each technology using a steelwork's number of furnaces using each technology.[19] Furthermore, I multiply the

[15]This is the upper limit of the raw material input per charge.

[16]To address new construction in the middle of the year, I weighted the capital data by the number of months of operation.

[17]The steelmaking firms use some scrap generated inside their steelworks, and the firms with blast furnaces produce pig iron themselves. In general, it is less expensive to use self-produced scrap and pig iron than to purchase it. Thus, the estimation results may exhibit downward bias in productivity. Estimating the cost of self-produced scrap and pig iron is an issue for future research.

[18]Heavy oil was divided into ranks A to C before 1961. However, there are only values of total heavy oil after 1962. Because rank-C oil was the most used before 1961, I regard all heavy oil as rank-C after 1962.

[19]The BOF can produce more crude steel given the same amount of time and capacity. Therefore, when considering the allocation of labor input between OHFs and BOFs, if the allocation is based on capacity, the labor input allocated to a BOF will be excessive. On the other hand, if the labor input is assigned based on the number of furnaces, it can be interpreted as the number of people per facility and considered not excessively allocated.

Table 1: Descriptive statistics : BOF

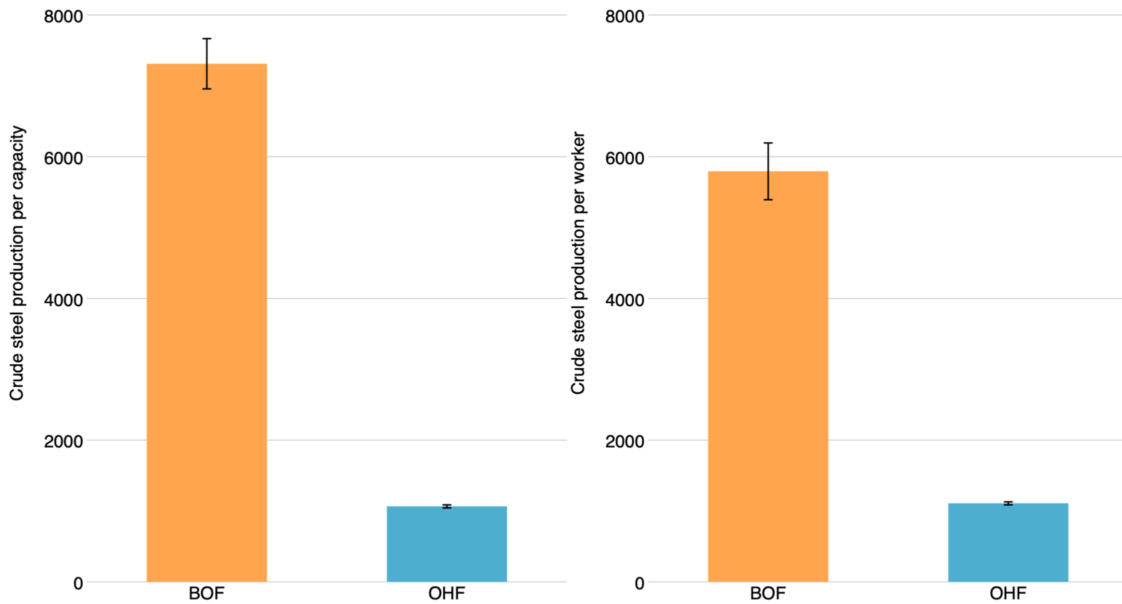
	BOF (N=256)			
	mean	sd	min	max
Production				
Crude Steel (t)	523,191	326,041	5,100	1,648,320
Capital				
Capacity (t/ch.)	73	38	30	180
Labor				
No. workers (pers.)	96	40	13	197
Energy				
Electricity (kWh)	9,373	12,694	120	80,722
Heavy oil (ℓ)	214	423	0	1,968
Material				
Scrap (t)	109,288	77,091	913	424,329
Pig iron (t)	457,344	285,446	0	1,387,518

Table 2: Descriptive statistics : OHF

	OHF (N=1,286)			
	mean	sd	min	max
Production				
Crude steel (t)	92,622	57,924	1,416	326,714
Capital				
Capacity (t/ch)	89	49	12	200
Labor				
No. workers (pers.)	83	47	0	371
Energy				
Electricity (kWh)	2,458	2,173	0	18,922
Heavy oil (ℓ)	5,160	2,968	0	21,439
Material				
Scrap (t)	38,853	22,274	0	134,770
Pig iron (t)	63,419	48,397	0	253,560

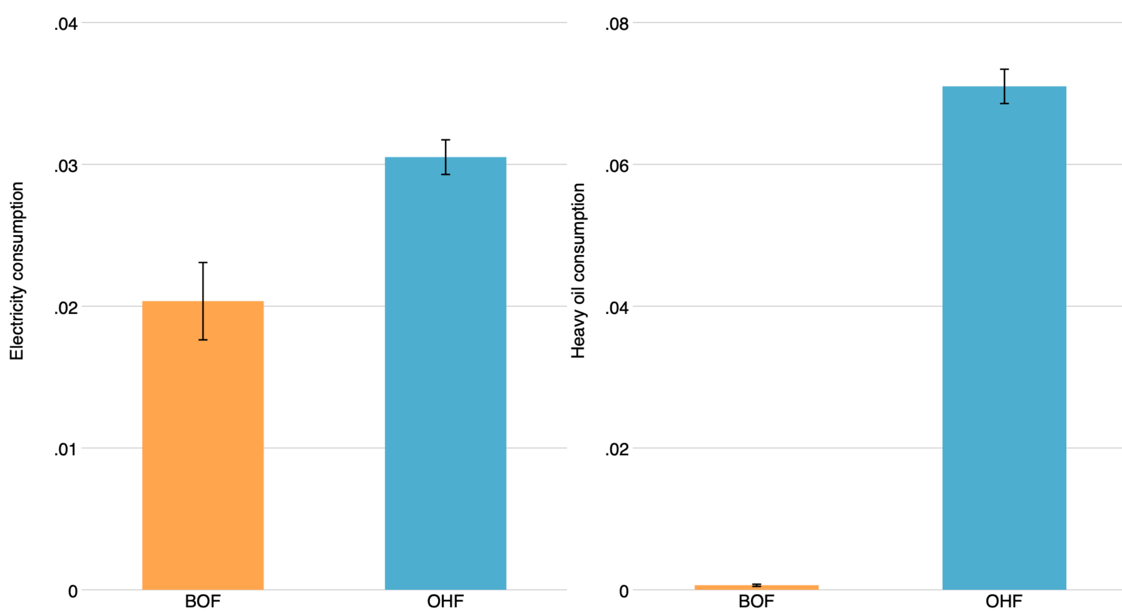
* N represents the sample size, that is, total furnace-years.
* All values listed are per furnace.
* The capacity of the furnace, t/ch, is the amount of intermediate material that can be fed in during one steel-making operation (called a "charge").

Figure 2: Crude steel production, per worker & per capacity



* The graphs show crude steel production per furnace capacity 1m^3 (= capital productivity) and per worker (labor productivity), respectively. Units are tons.
* Lines are confidence intervals.

Figure 3: Energy consumption per crude steel production (Electricity & Heavy oil)



* The graphs show electricity and heavy oil consumption per crude steel production. Units are kWh/t and ℓ/t, respectively.
* Lines are confidence intervals.

average working hours per worker.[20]

Descriptive statistics are listed in Table 1 for BOFs and Table 2 for OHFs. These are all per furnace. When comparing the amount of crude steel production between BOFs (Table 1) and OHFs (Table 2), I find that the BOFs produce over five times as much as the OHFs per furnace. For a more detailed comparison, crude steel production per furnace capacity and per worker is shown in Figure 2, and energy use per ton of crude steel is shown in Figure 3. The production per furnace capacity is seven times higher for BOFs than OHFs, and the production per worker is five times higher for BOFs than for OHFs. Since the advantage in production per furnace is greater than that in production per worker, it appears that the BOF is a capital-demanding and labor-saving technology. The amount of electricity and fuel oil used per ton of production in BOFs is low, 2/3 and 1/100, respectively, compared to OHFs. BOFs can produce more crude steel with less capacity (capital), labor, and energy input than OHFs. As mentioned in Section 2, BOFs appear to have operational advantages over OHFs. Based on this section's observational findings, the next section will construct a structural production function model and estimate it.

5 Production Function Estimation: Model and Results

This section explains the empirical model for estimating a production function that allows productivity to vary across technologies. Let $\psi \in \{OHF, BOF\}$ be a technology indicator. A panel composed of furnace $i = 1, ..., N$, over periods $t = 1, ..., T$, is observed. A furnace's output, capital and labor inputs are denoted by (Y_{it}, K_{it}, L_{it}), and their log values are denoted in lowercase by (y_{it}, k_{it}, l_{it}). A type ψ furnace-specific production technology is:

$$Y_{it} = F_{\psi,t}\left(K_{it}, L_{it}\right) \exp\left(\omega_{\psi,it}\right), \tag{1}$$

[20] The average working hours per worker are reported Japan Iron and Steel Federation (1955-1968a) at the firm-type level. The firm types are the blast furnace firm and the OHF firm. A blast furnace firm has blast furnace(s) and has either BOF(s) or OHF(s) or both in the refining process. An OHF firm has an OHF(s) but not a blast furnace.

where productivity $\omega_{\psi,it}$ is assumed to be Hicks-neutral and furnace specific.

Following the literature, I use the Cobb-Douglas specification in my estimation; then, the production function in logs for a type ψ furnace i at time t is as follows:

$$y_{it} = \beta_k^{\psi} k_{it} + \beta_l^{\psi} l_{it} + \omega_{\psi,it} + \varepsilon_{it} \tag{2}$$

where ε_{it} is an unanticipated i.i.d. shock to production.

5.1 Estimation Procedure

To estimate the production function (2), I must cope with two problems:

1.Simultaneity between input and productivity.

2.Selection bias whereby a lower productivity furnace tends to exit.

This paper employs the approach suggested by Ackerberg et al. (2015, henceforth ACF).

5.1.1 Addressing Simultaneity

The ACF framework for addressing simultaneity is called the control function approach. This approach relies on observable variables, such as investment, labor, and intermediate inputs, to proxy for unobserved productivity. In this analysis, I use the intermediate input (in logs) m_{it} as a control function.

ACF: 1st stage – the intermediate input demand of furnace i can be written as the following function:

$$m_{it} = m_{t,\psi}\left(k_{it}, l_{it}, \omega_{it}\right) \tag{3}$$

If m_{it} is assumed to be strictly increasing in ω_{it}, then one can invert the intermediate input demand function:

$$\omega_{\psi,it} = m_{\psi,t}^{-1}(.) = f_{\psi,t}\left(k_{it}, l_{it}, m_{it}\right) \tag{4}$$

By substituting $\omega_{\psi,it}$ in (2), the 1st stage estimation equation can be obtained.

$$\begin{aligned} y_{it} &= \beta_k^{\psi} k_{it} + \beta_l^{\psi} l_{it} + f_{\psi,t}\left(k_{it}, l_{it}, m_{it}\right) + \eta_{it} \\ \Leftrightarrow y_{it} &= \phi_{\psi,t}\left(k_{it}, l_{it}, m_{it}\right) + \eta_{it} \end{aligned} \tag{5}$$

Denote the information set as $\mathcal{I}_{it}$, and the 1st-stage moment condition is the following.

$$\mathrm{E}\left[\eta_{it} | \mathcal{I}_{it}\right] = \mathrm{E}\left[q_{it} - \phi_{\psi,t}\left(k_{it}, l_{it}, m_{it}\right) | \mathcal{I}_{it}\right] = 0 \tag{6}$$

The first stage plays a role in purging only the unanticipated shock to production η_{it} and in obtaining $\hat{\phi}_{\psi,t}$, the estimates of $\phi_{\psi,t}$. After this first stage, $\omega_{\psi,it}$ can be written as a function of $\boldsymbol{\beta}^{\psi} = \left(\beta_k^{\psi}, \beta_l^{\psi}\right)'$

$$\omega_{\psi,it} = \omega_{it}\left(\boldsymbol{\beta}^{\psi}\right) = \hat{\phi}_{\psi,t} - \beta_k^{\psi} k_{it} - \beta_l^{\psi} l_{it} \tag{7}$$

ACF: 2nd stage – Productivity is assumed to follow a Markov process, which means that productivity can be separated into an expected component g_{ψ} and an unexpected component ξ_{it}.

$$\begin{aligned} \omega_{\psi,it} &= \mathrm{E}\left[\omega_{\psi,it} | \mathcal{I}_{it-1}\right] + \xi_{it} = \mathrm{E}\left[\omega_{\psi,it} | \omega_{\psi,it-1}\right] + \xi_{it} \\ \Leftrightarrow \omega_{\psi,it} &= g(\omega_{\psi,it-1}) + \xi_{it} \end{aligned} \tag{8}$$

By substituting (8) into the production function, the following equation is obtained.

$$y_{it} = \beta_k^\psi k_{it} + \beta_l^\psi l_{it} + g(\omega_{\psi,it-1}) + \xi_{it} + \eta_{it}$$

Using $\hat{\phi}_{\psi,t}$, which was estimated in the first stage, the production function is rewritten as:

$$\begin{aligned} y_{it} =& \beta_k^\psi k_{it} + \beta_l^\psi l_{it} \\ &+ g\left(\hat{\phi}_{\psi,t-1}\left(k_{it-1}, l_{it-1}, m_{it-1}\right) - \beta_k^\psi k_{it} - \beta_l^\psi l_{it}\right) + \xi_{it} + \eta_{it} \end{aligned} \tag{9}$$

Then, the conditional moment condition (10) is:

$$\begin{aligned} &\mathrm{E}\left[\eta_{it} + \xi_{it} | \mathcal{I}_{it}\right] \\ &= \mathrm{E}\Big[y_{it} - \beta_k^\psi k_{it} - \beta_l^\psi l_{it} \\ &\quad -g\left(\hat{\phi}_{\psi,t-1}\left(k_{it-1}, l_{it-1}, m_{it-1}\right) - \beta_k^\psi k_{it} - \beta_l^\psi l_{it}\right) | \mathcal{I}_{it}\Big] = 0 \end{aligned} \tag{10}$$

Rewrite (10) to the moment condition to estimate parameter vector $\boldsymbol{\beta}^\psi$:

$$\mathrm{E}\left[\varepsilon_{it} \otimes \begin{pmatrix} 1 \\ k_{it} \\ l_{it-1} \\ \hat{\phi}_{\psi,t-1}(.) \end{pmatrix}\right] = 0 \tag{11}$$

where $\varepsilon_{it} = \xi_{it} + \eta_{it}$.

5.1.2 Addressing the Selection Bias

To cope with selection bias, define an indicator function $\chi_{\psi,it}$ that is equal to one if a type ψ furnace i is active and to zero if it exits. Let $\underline{\omega}_{\psi,it}$ be the threshold for a furnace to survive.

$\chi_{\psi,it}$ is written as

$$\chi_{\psi,it} = \begin{cases} 1 & \text{if } \omega_{\psi,it} \geq \underline{\omega}_{\psi,it} = \underline{\omega}_{\psi,t}\left(k_{it}\right) \\ 0 & \text{otherwise} \end{cases} \tag{12}$$

The cutoff rule differs across technologies.

Then the productivity process equation (8) must be rewritten as

$$\begin{aligned} \omega_{\psi,it} &= \mathrm{E}\left[\omega_{\psi,it} | \omega_{\psi,it-1}, \chi_{\psi,it} = 1\right] + \xi_{it} \\ \Leftrightarrow \omega_{\psi,it} &= g_{\psi}(\omega_{\psi,it-1}, \chi_{\psi,it} = 1) + \xi_{it} \end{aligned} \tag{13}$$

The survival probability is used to correct for selection bias in the following way. The survival probability is:

$$\begin{aligned} \Pr\left[\chi_{\psi,it} = 1 | \underline{\omega}_{\psi,t}, \mathcal{I}_{it-1}\right] &= \Pr\left[\omega_{\psi,it} \geq \underline{\omega}_{\psi,t}\left(k_{it}\right) | \underline{\omega}_{\psi,t}, \mathcal{I}_{it-1}\right] \\ &= \Pr\left[\omega_{\psi,it} \geq \underline{\omega}_{\psi,t}\left(k_{it}\right) | \underline{\omega}_{\psi,t}, \omega_{\psi,it-1}\right] \\ &= \rho_{t-1}\left(\underline{\omega}_{\psi,t}, \omega_{\psi,it-1}\right) \\ &= \rho_{t-1}\left(k_{it}, \phi_{\psi,t}, k_{it-1}, l_{it-1}\right) \equiv \mathcal{P}_{\psi,it} \end{aligned}$$

By using probit regression, the estimate of the survival probability $\hat{\mathcal{P}}_{\psi,it}$ is obtained.

Thus, I must consider the following productivity process in my model.

$$\omega_{\psi,it} = g\left(\omega_{\psi,it-1}, \mathcal{P}_{\psi,it}\right) + \xi_{it} \tag{14}$$

Therefore, the ACF 2nd stage production function is transformed as follows.

$$\begin{aligned} q_{it} &= \beta_k^{\psi} k_{it} + \beta_l^{\psi} l_{it} \\ &\quad + g\left(\hat{\phi}_{\psi,t-1}\left(k_{it-1}, l_{it-1}, m_{it-1}\right) - \beta_k^{\psi} k_{it} - \beta_l^{\psi} l_{it}, \mathcal{P}_{\psi,it}\right) + \xi_{it} + \eta_{it} \end{aligned} \tag{15}$$

Finally, the ACF 2nd stage unconditional moment, which considers both simultaneity and selection bias, can be written as follows.

$$\mathrm{E}\left[\varepsilon_{it} \otimes \begin{pmatrix} 1 \\ k_{it} \\ l_{it-1} \\ \hat{\phi}_{\psi,t-1}(.) \\ \hat{\mathcal{P}}_{\psi,it}(.) \end{pmatrix}\right] = 0 \tag{16}$$

5.2 Production Function Estimation Results

Using the ACF procedure explained in the previous subsection, I estimate the production function with and without accounting for the technology heterogeneity. The estimation results are shown in Table 3. Column 1 is the result of the homogeneous production function, while columns 2 to 4 are technology-specific results. "Capital × BOF" and "Labor × BOF" represent the interaction terms between each input and the BOF dummy, which indicate the technological difference in using inputs between BOF and OHF technology. Column 2 reports the technology-specific result without controlling for selection by entries and exits, whereas the other columns report results when controlling for selection.

According to a comparison of Column 1 with Columns 3 and 4, as the BOF interaction terms are statistically significant, the production functions of the BOF and OHF are considered to be different. Similarly, the standard errors in the technology-specific production function are smaller than those in the homogeneous estimation. Among the technology-specific results, the estimated values of the interaction terms are more stable when controlling for selection in Column 3 than when not doing so in Column 2, which suggests that the correction for selection bias is working well. The polynomial and kernel control functions in Column 3 and Column 4, respectively, have similar coefficients, but the kernel results yield smaller standard errors. To reduce the computational burden, I treat the polynomial results as the baseline. In the following calculations, I use this baseline result.

Table 3: Production function : Estimation results

	Pooled	Tech-specific		
	(1)	(2)	(3)	(4)
Capital	0.281	0.446***	0.281*	0.297***
	(0.516)	(0.040)	(0.161)	(0.107)
Labor	0.618***	0.579***	0.618***	0.614***
	(0.120)	(0.049)	(0.094)	(0.085)
Capital × BOF		0.833	0.811***	0.791***
		(4.324)	(0.159)	(0.056)
Labor × BOF		−0.214	−0.388***	−0.355***
		(0.237)	(0.105)	(0.085)
ϕ function	polynominal	polynominal	polynominal	kernel
Selection correction	X		X	X
N	1507	1507	1507	1507

* Standard errors in parentheses. Asterisks indicate the significance level; * at 10 percent, ** at 5 percent, and *** at 1 percent.
* BOF is a dummy variable; it takes value one if a furnace uses BOF technology.
* In "Tech-specific" estimation, I include cross term of the inputs and BOF dummy. In "Pooled", I do not. All results are estimated by using the ACF-type method.
* "ϕ function" is control function in the first-stage estimation.
* In the "Selection correction" row, X means that I correct for selection bias caused by entries and exits.
* Standard errors are clustered at the furnace level, and in the ACF, they are calculated by block bootstrap to correct for the bias caused by using two-step estimation.

Regarding the differences in the BOF and OHF coefficients, the coefficient of capital is approximately 0.8 larger and that of labor is about 0.4 smaller in the BOF than in the OHF. This difference indicates that the BOF is a more capital-intensive and labor-saving technology than the OHF. Moreover, because the sum of the capital and labor coefficients is larger than zero, introducing BOF technology appears to be the capital-augmenting technological progress.

Although Collard-Wexler and De Loecker (2015) estimated ACF technology-specific production functions similar to those in this study, their technology interaction terms are insignificant. In contrast, this study finds that the new technology production function is significantly different from old function. One possible explanation for this difference is that

Table 4: BOF advantage in productivity

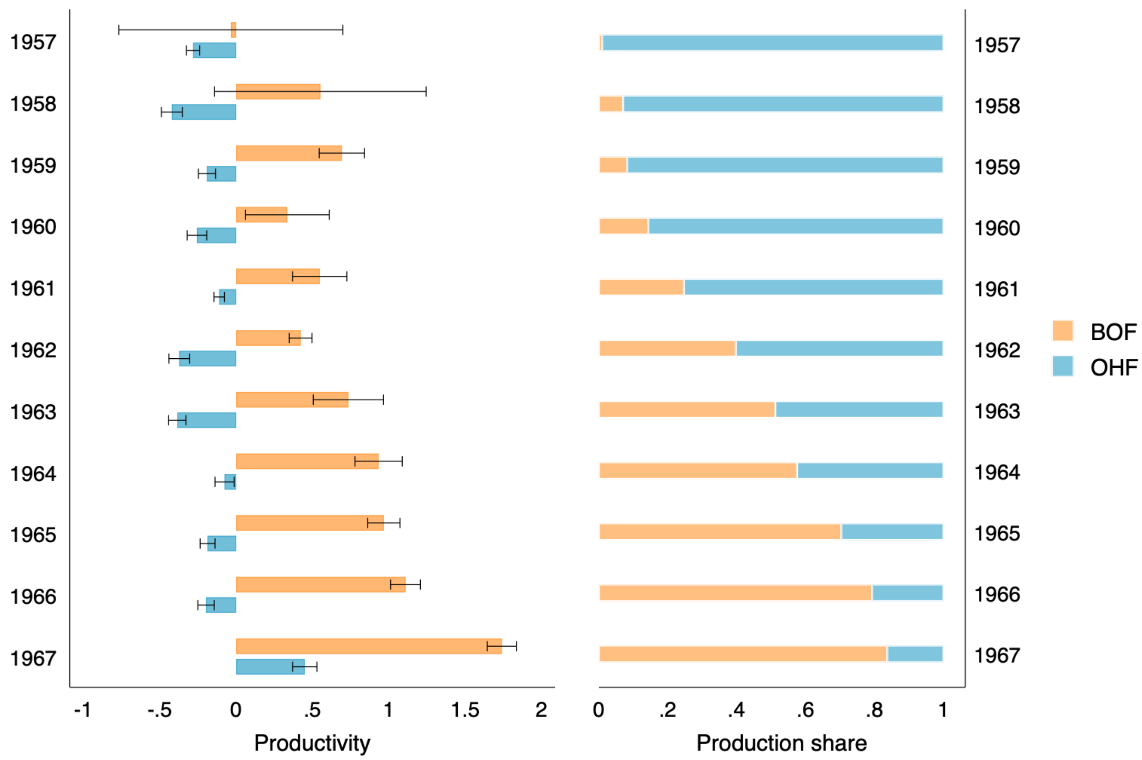
	Productivity ω			
	(1)	(2)	(3)	(4)
BOF dummy	1.506***	1.036***	1.082***	1.545***
	(0.027)	(0.029)	(0.023)	(0.025)
Fixed effect				
furnace	X			X
firm × Year		X		X
plant × Year			X	X
N	1505	1505	1505	1505
Adj. R^2	0.789	0.827	0.928	0.871

* This analysis uses the productivity estimated in Column 3 of Table 3, the baseline result of this study.
* The BOF dummy indicates the BOF's average productivity advantage against the OHF in each specification.
* Fixed effects: Year fixed effects are controlled for in all specifications. Furnace means that there are furnace dummies in the estimation. Firm × year means that firm dummies, year dummies, and interaction terms of the firm and year dummies are included; the same is the case for plant × year and technology × year.

they consider the entire steelworks from material to the final product, while this study focuses on a single steel-refining process. Additionally, because they use value-based output and capital input, various products and facilities' importance are aggregated, and the technological difference may be difficult to identify. By contrast, since the present analysis is at the facility level, the technology difference may be easy to identify. Another possible explanation is that BOF technology represented such a drastic improvement that it was able to replace OHF technology in the steel-refining process.

To examine the advantage of BOF against OHF, I regress the BOF dummy on computed productivity $\hat{\omega}_{it}$ while controlling for year and furnace fixed effects. The advantage of BOF over OHF is represented by the term "BOF dummy" in Table 4. In other words, the BOF dummy represents the difference in (unweighted) average productivity between technologies. Although the BOF productivity advantage decreases with additional fixed effects, the BOF advantage does not vanish when controlling for firm and plant heterogeneity and technology-

Figure 4: Productivity trend by technology



* In the left graph, the bars represent the productivity levels, and the lines represent the 95% confidence intervals.

* Productivity is demeaned by industry total sample averages (not technology-specific averages)

Table 5: Productivity change by technology

	BOF		OHF		(BOF)-(OHF)
	Productivity	No.	Productivity	No.	Productivity
1957	−0.073	2	−0.276	121	+0.209
	(0.533)		(0.242)		[−0.099, 0.594]
1958	0.517	2	−0.415	117	+0.938
	(0.503)		(0.378)		[0.437, 1.508]
1959	0.659	5	−0.185	115	+0.850
	(0.169)		(0.307)		[0.609, 1.158]
1960	0.301	10	−0.250	128	+0.558
	(0.442)		(0.370)		[0.348, 0.836]
1961	0.511	16	−0.104	127	+0.622
	(0.365)		(0.196)		[0.543, 0.774]
1962	0.390	24	−0.366	126	+0.763
	(0.186)		(0.389)		[0.634, 0.956]
1963	0.704	28	−0.379	122	+1.090
	(0.616)		(0.320)		[0.958, 1.284]
1964	0.901	31	−0.069	116	+0.977
	(0.441)		(0.344)		[0.863, 1.155]
1965	0.937	41	−0.181	109	+1.124
	(0.344)		(0.259)		[1.052, 1.258]
1966	1.079	44	−0.190	88	+1.276
	(0.330)		(0.257)		[1.203, 1.409]
1967	1.710	53	0.456	80	+1.261
	(0.351)		(0.363)		[1.166, 1.417]
Average	0.972	–	−0.199	–	+1.178
	(0.587)		(0.376)		[1.153, 1.266]

* Productivity is demeaned by sample average (not technology-specific averages)
* No. represents the number with furnaces of each technology in each year.
* The last column, (BOF) - (OHF), indicates the average productivity difference between the BOF and OHF. It takes a positive value (+) if BOF productivity is higher than that of OHF.

year idiosyncratic effects.

Table 5 and Figure 4 illustrate the annual trends in average productivity for each technology. As BOFs expand their share, the BOF productivity and BOF average productivity advantage over OHFs increase. Moreover, as Nakamura (2007) noted, the stability of BOFs increased as BOF productivity and the BOF share increased. Nakamura and Ohashi (2012b)'s Figure 5, which displays productivity trends by each technology, and Figure 4 of this study are similar. In both studies' results, BOF productivity multiplies, and OHF productivity does not change substantially.[21] Therefore, the productivity estimation result of this study is considered reasonable. I use the estimated productivity results to decompose the causes of the productivity increase in the next section.

6 Decomposition Analysis

In this section, I decompose the factors of productivity growth both within and between technologies and quantitatively analyze both the operational improvement effect and the reallocation effect. First, I conduct a static decomposition. The static method decomposes the aggregate productivity change into two categories: producer-level unweighted average productivity and the covariance of production share and productivity. By using this covariance term, I can check whether production is reallocated to more productive furnaces.

In addition, I implement dynamic decomposition. In dynamic decomposition, the reallocation effect is further decomposed into reallocation among incumbents and reallocation through entry and exit. By conducting dynamic decomposition, I can analyze the impact of the entry of new BOF furnaces with high productivity and the exit of low-productivity old OHF furnaces.

[21] Since their observation unit is the steelworks-technology, their production function specification is gross-output, and the inputs used are different; hence, the coefficients are not comparable.

6.1 Static Decomposition

In the static decomposition, I introduce three decomposition methods: industry-wide, within-technology, and between-technology decomposition. With the industry-wide decomposition, I obtain an overview of which is more critical, average furnace productivity growth or reallocation. Furthermore, to delve deeper into the effect of technology — the main focus of this paper — the between-technology decomposition analyzes the effect of production reallocation from old to new technology on productivity growth, and the within-technology decomposition examines allocation efficiency within each technology.

6.1.1 Static Decomposition: Definition

Using the furnace i time t productivity ω_{it} and production share s_{it}, the aggregate industry productivity can be written as $\Omega_t \equiv \sum s_{it}\omega_{it}$. Then, the Olley and Pakes (1996) type industry-wide decomposition is defined as follows [22].

Method 1: Industry-Wide (Olley-Pakes) Decomposition.

$$\Omega_t = \underbrace{\overline{\omega}_t}_{\text{operational improvement effect}} + \underbrace{\sum_i \left(\omega_{it} - \overline{\omega}_t\right)\left(s_{it} - \overline{s}_t\right)}_{\text{production reallocation effect}} = \overline{\omega}_t + \Gamma_t^{OP} \tag{17}$$

In equation (17), $\overline{\omega}_t$ is the unweighted average productivity and expresses the effect of improvement in furnace operation. I call this the "operational improvement effect". Γ_{OP} is the covariance between productivity and the production share, and a positive change in Γ_{OP} indicates a reallocation of production to more productive furnaces. I refer to this as the "production reallocation effect", or simply, the "reallocation effect".

The Olley-Pakes decomposition formula (17) can be applied to each technology separately: this decomposition is within-technology decomposition. Denote the unweighted average productivity of technology ψ as $\overline{\omega}_t(\psi)$ and the production share of technology ψ as

[22] I follow Collard-Wexler and De Loecker (2015) regarding the notations and definitions.

$s_t(\psi)$. These are calculated using formulae $\overline{\omega}_t(\psi) = \frac{1}{N_t(\psi)} \sum_{i \in \psi} \omega_{it}$ and $s_t(\psi) = \sum_{i \in \psi} s_{it}$, respectively. Then the within-technology decomposition is as follows.

Method 2: Within-Technology Decomposition.

$$
\begin{aligned}
\Omega_t &= \sum_{\psi \in BOF, OHF} s_t(\psi) \left(\overline{\omega}_t(\psi) + \sum_{i \in \psi} \left(\omega_{it} - \overline{\omega}_t(\psi)\right) \left(s_{it}(\psi) - \overline{s}_t(\psi)\right) \right) \\
&= \sum_{\psi \in BOF, OHF} s_t(\psi) \left(\underbrace{\overline{\omega}_t(\psi)}_{\text{Operation improvement of technology } \psi} + \underbrace{\Gamma_t^{OP}(\psi)}_{\text{Reallocation within technology}} \right) \qquad (18)
\end{aligned}
$$

With the within-technology decomposition, I can calculate both the operational improvement and reallocation effects of new and old technologies. This decomposition allows me to analyze the extent to which the average productivity of BOFs increased compared to OHFs, and the difference in the allocative efficiency of both technologies.

Finally, I define the between-technology decomposition that expresses the reallocation effect from OHFs to BOFs through the spread of BOFs. The simple average productivity of BOFs and OHFs is written as $\overline{\Omega}_t = \frac{1}{2} \sum_{\psi} \Omega_t(\psi)$[23]. Then, the between-technology decomposition is as follows:

Method 3: Between-Technology Decomposition.

$$
\begin{aligned}
\Omega_t &= \overline{\Omega}_t + \sum_{\psi \in BOF, OHF} \left(s_t(\psi) - 1/2\right) \left(\Omega_t(\psi) - \overline{\Omega}_t\right) \\
&= \underbrace{\overline{\Omega}_t}_{\text{Average productivity improvement of two technologies}} + \underbrace{\Gamma_t^B}_{\text{Between technology reallocation effect}} \qquad (19)
\end{aligned}
$$

Γ_t^B is the between-technology covariance of productivity and production share. The higher the rate of increase in Γ_t^B is, the more production is reallocated to the productive technology (in this case, the BOF).

Within- and between-technology decomposition can be combined in a single equation.

[23] The 1/2 indicates the value when the BOF and OHF had the same share, that is, exactly the simple average value.

First, $\overline{\Omega}_t$ can be written as

$$\bar{\Omega}_t = \frac{1}{2}\sum_{\psi}\Omega_t(\psi) = \frac{1}{2}\sum_{\psi}\sum_{i\in\psi}s_{it}(\psi)\omega_{it}$$
$$\Leftrightarrow \quad \bar{\Omega}_t = \frac{1}{2}\sum_{\psi\in BOF,OHF}\left(\bar{\omega}_t(\psi) + \Gamma_t^{OP}(\psi)\right). \tag{20}$$

By substituting equation (20) into equation (19),

$$\Omega_t = \frac{1}{2}\sum_{\psi\in BOF,OHF}\Bigg[\underbrace{\overline{\omega}_t(\psi)}_{\text{operation improvement by }\psi} + \underbrace{\Gamma_t^{OP}(\psi)}_{\text{Reallocation within technology}}\Bigg] + \underbrace{\Gamma_t^{B}}_{\text{Between technology reallocation}} \tag{21}$$

Using equation (21), the following three effects can be comprehensively compared: (1) the average operational improvement of each technology, (2) the within-technology production reallocation effect, and (3) the between-technology production reallocation effect.

6.1.2 Static Decomposition: Results

The static results for Olley-Pakes, between-technology, and within-technology decomposition are shown in Table 6. Based on the Olley-Pakes and the between-technology decomposition, the operational improvement effects account for approximately 70% of the total, indicating that the increase in industry average productivity due to operational improvement is the primary factor in productivity growth in the steel industry. The increase in average productivity due to operational improvements is a significant factor in productivity growth.

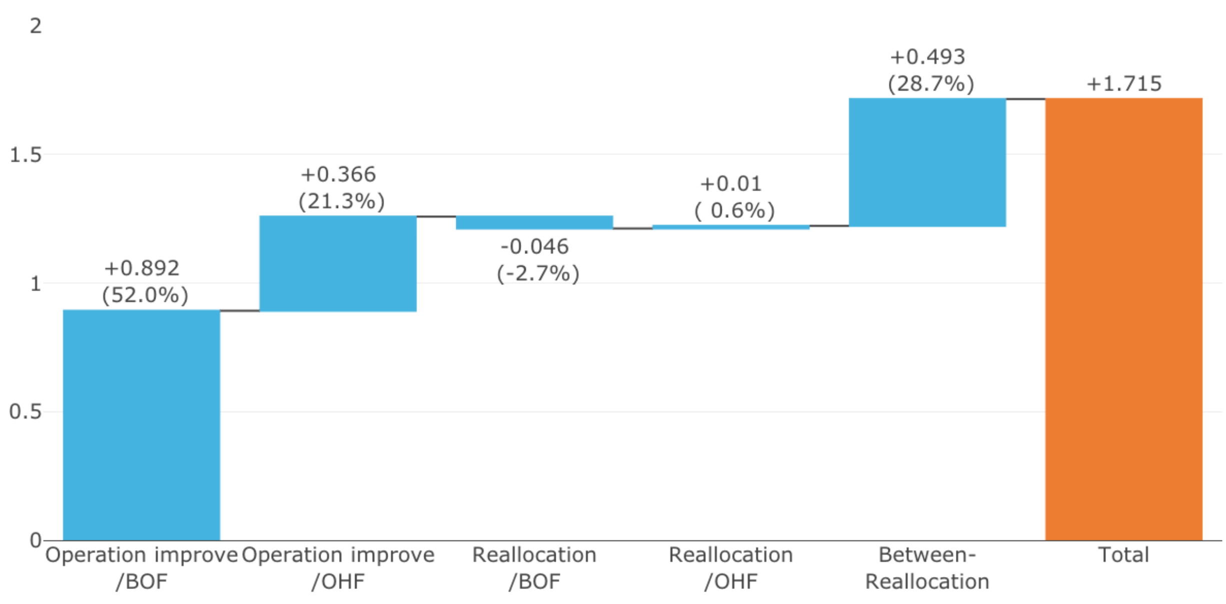
Figure 5 shows the decomposition result for operational improvement and the within-reallocation effects by technology and the between-technology reallocation effect, as defined in equation (21). The factor with the most outstanding contribution is the operational improvement of the BOF, which accounts for 52% of aggregate productivity growth. The second-largest factor is the between-technology reallocation, which accounts for 29% of productivity growth. The production reallocation from OHFs to BOFs had an essential impact

Table 6: Static Decomposition

$\Delta\Omega_t$	1.715			
Olley-Pakes:				
Operational improvement: $\overline{\omega}_t$	1.228	(71.6%)		
Reallocation effect: Γ_t^{OP}	0.486	(28.4%)		
Between-Technology:				
Operational improvement: $\overline{\Omega}_t$	1.221	(71.2%)		
Reallocation effect: Γ_t^{B}	0.493	(28.8%)		
Within-Technology:	BOF		OHF	
Total Growth	1.692		0.751	
Operational improvement: $\overline{\omega}_t(\psi)$	1.783	(105.4%)	0.732	(97.4%)
Reallocation effect: $\Gamma_t^{OP}(\psi)$	-0.091	(-5.4%)	0.019	(2.6%)

* The share of each factor in productivity change is in parentheses.

Figure 5: Static Decomposition



* The figures in parentheses show the share of each factor in aggregate productivity growth.
* As equation (21) shows, the contribution of within-technology decomposition terms to the aggregate productivity growth is calculated using half the value in the Table 6.

on the increase in aggregate productivity.

6.2 Dynamic Decomposition

The static decomposition results revealed that reallocation effects, especially between technologies, are an important factor that accounts for nearly 30 percent of total aggregate productivity growth. However, the reallocation effect in the static decomposition includes both the reallocation effect among incumbent furnaces and through the entry and exit of furnaces. In the industry overview, I mentioned that many new furnaces were built throughout the spread of BOF technology. This means that it is also important to analyze the effects of the new construction of BOF furnaces. Therefore, in this subsection, I conduct a dynamic decomposition of productivity growth, taking into account the effect of entry and exit.

6.2.1 Dynamic Decomposition: Definition

Let $\Delta\Omega_t$ be the aggregate productivity growth of the industry. Denote the three groups of furnaces as incumbents $\mathcal{I}$, entrants $\mathcal{N}$, and exiters $\mathcal{X}$ and each group's aggregate productivity at time t as $\Omega_t^{\mathcal{I}}$, $\Omega_t^{\mathcal{N}}$, and $\Omega_t^{\mathcal{X}}$, respectively. Using these group notations, the dynamic decomposition of $\Delta\Omega_t$ can be defined as

Dynamic decomposition[24]

$$\begin{aligned}\Delta\Omega_t &= \Omega_t^{\mathcal{I}} - \Omega_{t-1}^{\mathcal{I}} + \Omega_t^{\mathcal{N}} - \Omega_{t-1}^{\mathcal{X}} \\ &= \underbrace{\sum_{i\in\mathcal{I}} s_{it-1}\Delta\omega_{it}}_{\text{Operation improvement}} + \underbrace{\underbrace{\sum_{i\in\mathcal{I}} \Delta s_{it}\omega_{it-1}}_{\text{Reallocation}} + \underbrace{\sum_{i\in\mathcal{I}} \Delta s_{it}\Delta\omega_{it}}_{\text{Covariance}}}_{\text{Reallocation effect}} \\ &\quad + \underbrace{\sum_{i\in\mathcal{N}} s_{it}\omega_{it}}_{\text{Entry}} - \underbrace{\sum_{i\in\mathcal{X}} s_{it-1}\omega_{it-1}}_{\text{Exit}} \end{aligned} \tag{22}$$

[24]In the dynamic decomposition accounting for entry and exit, I use the method suggested by Davis et al. (1996) and employed in Collard-Wexler and De Loecker (2015), among others.

The first term represents the effect of operational improvement, the sum of the second and third terms represents the effect of production reallocation, the fourth term represents the entry effect through new furnace construction, and the fifth term represents the exit effect through furnace retirement. Both entry and exit effects are evaluated as deviations from the previous period's average productivity, with a positive contribution to productivity growth when a furnace with above-average productivity enters the market or when a furnace with below-average productivity exits the market.[25]

Dynamic decomposition is conducted both within- and between-technology as in the static decomposition. Analogous to equation (21) in the static decomposition, the dynamic decomposition can summarize the within- and between-technology decomposition in one equation. According to the static between-decomposition formula (19), the productivity change in period t is:

$$
\begin{aligned}
\Delta\Omega_t &= \Omega_t - \Omega_{t-1} \\
&= \left(\bar{\Omega}_t + \Gamma_t^B\right) - \left(\bar{\Omega}_{t-1} + \Gamma_{t-1}^B\right) = \left(\bar{\Omega}_t - \bar{\Omega}_{t-1}\right) + \underbrace{\left(\Gamma_t^B - \Gamma_{t-1}^B\right)}_{\Delta\Gamma_t^B} \\
&= \frac{1}{2}\sum_{\psi \in BOF,OHF} \left(\Omega_t(\psi) - \Omega_{t-1}(\psi)\right) + \Delta\Gamma_t^B \\
&= \frac{1}{2}\sum_{\psi \in BOF,OHF} \left(\Omega_t^{\mathcal{I}}(\psi) - \Omega_{t-1}^{\mathcal{I}}(\psi) + \Omega_t^{\mathcal{N}}(\psi) - \Omega_{t-1}^{\mathcal{X}}(\psi)\right) + \Delta\Gamma_t^B
\end{aligned}
$$

Because the terms within the bracket is the exactly the form of the dynamic decomposition

[25]Because productivity is demeaned by the industry total average $\bar{\omega}$, the following terms are deviations from the industry average for the entire period in practice : the reallocation term, $\sum_{i\in\mathcal{I}} \Delta s_{it}(\omega_{it-1} - \bar{\omega})$, the entry term, $\sum_{i\in\mathcal{N}} s_{it}\omega_{it}$, and the exit term, $\sum_{i\in\mathcal{X}} s_{it-1}(\bar{\omega} - \omega_{it-1})$. By demeaning productivity, the entry and exit effects can be evaluated as a real contribution. Otherwise, whenever there is an entry, it will be expressed as contributing to productivity growth.

formula (22),

$$\Delta\Omega_t = \frac{1}{2} \sum_{\psi \in BOF,OHF} \left(\sum_{i \in \mathcal{I}} s_{it-1}(\psi)\Delta\omega_{it} + \sum_{i \in \mathcal{I}} \Delta s_{it}(\psi)\omega_{it-1} + \sum_{i \in \mathcal{I}} \Delta s_{it}(\psi)\Delta\omega_{it} \right.$$
$$\left. + \sum_{i \in \mathcal{N}} s_{it}(\psi)\omega_{it} - \sum_{i \in \mathcal{X}} s_{it-1}(\psi)\omega_{it-1} \right) + \Delta\Gamma_t^B. \tag{23}$$

In the following subsection, I will use this formula to compare each technology's operational improvement, within-reallocation, entry-exit, and between-technology reallocation effects.

6.2.2 Dynamic Decomposition: Results

Applying equation (22) to all furnaces pooled and by technology, Table 7 shows the dynamic decomposition results. Compared to the static decomposition results, the dynamic factor – the entry-exit premium – represents over one-quarter of the aggregate productivity growth. This result suggests that the construction of new furnaces is a crucial factor that we should not ignore when analyzing the effect of introducing new technology on productivity. As in the static decomposition, the ratio of operational improvement to reallocation effects is approximately seven to three.

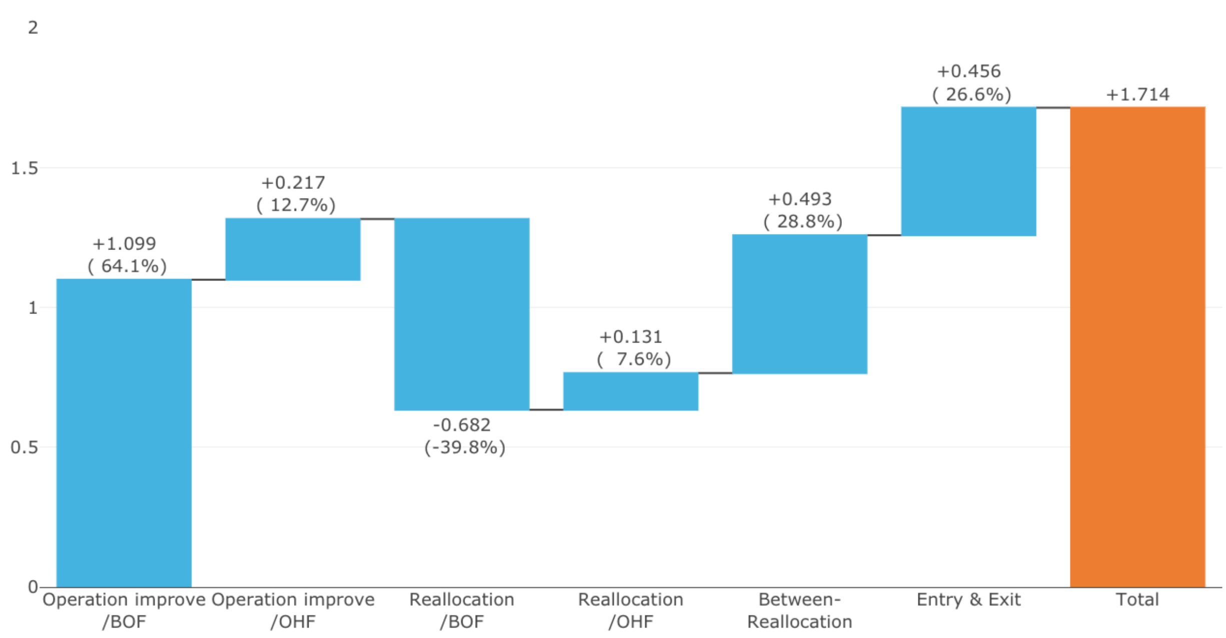
Figure 6 displays the technology-specific decomposition result for operational improvement and within-reallocation effects by technology, between-technology reallocation, and entry-exit effects defined in equation (23). Regarding the technology-specific decomposition, the BOF operational improvement has the highest contribution to aggregate productivity growth (a 64.1% share). The between-technology reallocation to existing and newly constructed furnaces combined accounts for a 50% share of aggregate productivity growth. Thus, both operational improvement and between-technology reallocation had a substantial impact on aggregate productivity growth in this period. On the other hand, it is also remarkable that within-BOF reallocation has a considerably negative impact with a -39.8% share.

Table 7: Dynamic Decomposition

$\Delta\Omega_t$	1.715			
Across all furnace:				
Operational improvement	0.990	(57.8%)		
Reallocation	0.330	(19.2%)		
Entry-Exit premium	0.394	(23.0%)		
Technology-Specific:				
Within-technology part	1.221	(71.2%)		
Between-reallocation	0.493	(28.8%)		
Within-Technology:	BOF		OHF	
Total Growth	1.692	(49.3%)	0.751	(21.9%)
Operational improvement	2.199	(64.1%)	0.434	(12.7%)
Reallocation	−1.364	(−39.8%)	0.263	(7.7%)
Entry-Exit premium	0.857	(26.6%)	0.040	(2.4%)

* Share of each factor in productivity change is in parentheses.

Figure 6: Dynamic decomposition: Each factor contribution



* The figures in parentheses show the share of each factor in aggregate productivity growth, using the results in Table 7
* As equation (23) shows, the contribution of the within-technology decomposition terms to the aggregate productivity growth is calculated using half the value in Table 7.

6.3 Interpretation –What is the Productivity Growth Driver?–

What do the decomposition results indicate to the research question, namely, what is the most important productivity growth driver when a promising new technology arrives? The answer is that operational improvement and reallocation to the new technology are considered as equally essential when adopting new technology. This subsection will discuss the policy and industrial background that might be responsible for each of the two factors.

The fundamental factor that caused production reallocation to the new technology furnaces is presumed to be industry-wide license sharing. The government's intervention allowed the use of BOF technology throughout the steelmaking industry, not just a few firms. Other factors that lowered the barriers to introducing BOF technology are the lower cost of licensing fees than in other countries and the government's tax incentives for BOF equipment.

The critical factor that may be responsible for the operational improvement was technological improvement in the BOF technology, including inventions developed by Japanese steelmakers. Since the BOF was no more than one of many promising technologies, technological advances were essential for it becoming the major production technology. Previous research in the literature Nakamura and Ohashi (2012a) reports that steelworks that introduced two major inventions that improved BOF efficiency were 30% more productive.

Another notable factor that contributed to both reallocation and operational improvement is knowledge share. Leading firms shared their operational knowledge with latecomers in various ways. For example, they shared the improved technologies they invented and transferred the operational experience through steelworks visits. Under the license agreement, the entire industry could share knowledge, and the engineering staff of each firm actively discussed new technological updates at industry conferences. These situations are presumed to have improved the productivity of each firm's furnaces and increased their willingness to adopt BOF technology.

On the other hand, the aforementioned factors may have reduced allocative efficiency within the BOF because the within-BOF reallocation effect represented a -39.8% productivity change in the dynamic decomposition analysis. As a result of making it easier for firms to adopt BOF, firms with inferior capabilities could also adopt BOF technology. Because of this situation, the within-BOF allocation efficiency may have deteriorated. Nevertheless, the BOF average growth and between-reallocation account for 78.1% of the aggregate productivity growth share. Thus, on the whole, the Japanese government's policy package would be effective and successful in spreading new technology with high operational improvement growth.

In this period, average OHF productivity growth was one-fifth of the BOF's.[26] There was some OHF improvement, but the gap with BOFs gradually widened, and the advantage of BOFs became evident. Although easy access to BOF technology worsened the within-BOF allocative efficiency, it allowed all firms and steelworks to benefit from the BOF's rapid productivity growth from intensive operational improvement.

According to the World Bank (Cirera and Maloney, 2017), although the benefits of introducing new technologies are high in developing countries, their adoption has been slow. They noted that one of the problems responsible for such situations is the lack of effective use of limited government resources to design policy. During the period of analysis, Japan was a developing country, and therefore, present-day developing countries might benefit from examining the Japanese policy package that achieved both fast new technology diffusion and rapid productivity growth.

7 Conclusion

This paper investigates the impact of new technology on productivity growth when the new technology rapidly spreads and replaces old technology. I analyzed the introduction of BOF technology in the Japanese steel industry during the 1950s to 1960s as a case study. I employ the ACF-type approach to estimate a production function that considers technology heterogeneity. Using estimated productivity, I decompose productivity growth into four factors:

[26] The average productivity growth was equal to the operational improvement term.

(i) operational improvement, (ii) between-technology reallocation, (iii) within-technology reallocation, and (iv) entry-exit.

First, each technology's productivity estimation results show that the new BOF technology had advantages in productivity and in the growth rate over the old OHF technology. The estimation results confirm previous descriptive analyses; the BOF's superior productivity relative to the OHF widened as BOF productivity stabilized.

The decomposition analysis reveals substantial factors responsible for productivity growth are BOF operational improvement and between-technology reallocation, accounting for approximately 65% and 50% of the total, respectively. Hence, operational improvement and reallocation are equally essential when adopting new technology. Moreover, the entry-exit effect accounts for a non-negligible half of the between-reallocation effect, which is not examined separately in previous research. Conversely, within-BOF allocative efficiency worsened by approximately 40% of productivity growth. Combining government policies and firms' technological inventions may have promoted to increase productivity and industrial development while worsening within-allocation.

Although this paper provides a unified and quantitative comparison of what factors contribute to productivity growth when new technology rapidly spreads, I cannot directly measure the policy effect on productivity and welfare. To apply the Japan's past experience as a developing country to the current environment and present-day developing countries, it is necessary to conduct policy evaluation through structural estimations. A dynamic structural estimation considering plants' new furnace construction and divestment decisions on each technology will be able to quantify how much faster firms introduce the BOF furnaces than without license sharing, tax exemption, and so forth. Furthermore, I did not include the sharing of operational knowledge and improvement technologies among competing firms in the model. It would be valuable to estimate the production function with knowledge spillovers among firms or plants.

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