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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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Abstract

This paper analyzes the effect of new technology for steel refining—the basic oxygen furnace—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 are both substantially important: (i) the rapid operational progress of new technology and (ii) between-technology reallocation both among existing furnaces and through entries. I also find that although the overall allocation efficiency improved, the within-new-technology allocation efficiency declined. The results suggest that government policies encouraged the construction of new furnaces by lowering the cost of introducing new technology, and firms were able to enjoy the high productivity gains from the new technology itself and its rapid growth.

Keywords: New technology, Productivity, Productivity decomposition, Allocation, Between-technology reallocation

1 Introduction

New technology is viewed as one of the major sources of economic and 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? How can government facilitate technology adoption and promote economic progress?

This paper analyzes the effect of new technology on productivity using the Japanese steel industry of the 1950s to the 1960s as a case study. The Japanese steelmaking industry during this period is regarded as a successful example of industry growth through the introduction of a new refining technology—the basic oxygen furnace (hereafter BOF). 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 70% in the later 1960s. The Japanese steelmaking industry achieved rapid

growth from the late 1950s to the early 1970s, with a tenfold increase in crude steel production from 1957 to 1973 and a 16-fold increase in steel exports from 1957 to 1969.

In this period, the Japanese government implemented policies to facilitate the spread of the BOF, and Japanese steelmakers made efforts to improve BOF technology. An important example is that the Japanese government had coordinated during the license negotiation between overseas licensers to ensure that the BOF license would not be an exclusive contract by one firm, but a contract that the entire Japanese steelmaking industry could use. In addition to eliminating barriers to access to the BOF license, the government encouraged BOF adoption through various policies, including tax reductions. When the BOF was first introduced in Japan, there were many operational challenges, but Japanese steelmakers enhanced BOF performance by developing improved technologies. This might have promoted the spread of BOFs and increased productivity. Furthermore, operating knowledge and operating experience, including improved technologies, were shared across the industry, primarily from first-movers who were early adopters of BOF. It is worth investigating how this situation affected BOF diffusion, and productivity growth through production reallocation.

Utilizing detailed facility (furnace) level data, this study estimates a production function that considers technology heterogeneity, and decomposes productivity growth factors by using the estimated productivity. I decomposed the productivity growth into the following four factors: (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 (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). Based on results of the productivity decomposition analysis, I explore the effect of government policies and industry situations on new facility construction and production reallocation.

The decomposition analysis results indicate that the primary factor that induced productivity growth was operational improvements to the BOF which accounted for more than 55% 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 around 35% shares, for a total of 70%. On the other hand, the allocative efficiency within the BOF technology worsened by nearly 45%. Moreover, additional analyses suggest that government policies facilitated a smooth transition to new BOF technology by supporting new furnace construction not only by first-movers, but also by other firms. Although this worsened within-BOF reallocation because new furnaces tended to have lower productivity within BOFs, all firms could receive industry-wide productivity growth through the operational improvement of BOF furnaces.

This paper contributes to two strands of literature. The first consists of papers identifying the source of productivity change and productivity differences across various entities (see Syverson 2011, for a comprehensive survey). In particular, this study is related to papers that focus on the role of technology (e.g., Collard-Wexler and De Loecker 2015; Oster 1982; Van Biesebroeck 2003). This study is most closely related to 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, electric arc furnace)—and analyze the sources of industrial productivity growth via a decomposition method.[1][2]

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, numerous studies exist, both descriptive (see e.g., Lee and Ki 2017; Lynn 1981, 1982; Nakamura 2007) and quantitative (see e.g., Nakamura and Ohashi 2008, 2012a, b; Ohashi 2005; Okazaki and Korenaga 2015). Among the descriptive studies, Lynn (1982) suggested the role of government, and Nakamura (2007) investigates various aspects of technological history. Among the quantitative studies, 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 invented by Japanese companies after the introduction of the BOF. Their paper reports that these two improved technologies explained 30% of the productivity increase.[3]Nakamura and Ohashi (2012b) investigate the intra- and inter-plant diffusion patterns and productivity growth.[4] Nakamura and Ohashi (2008) focused on learning-by-doing in the adoption of BOF technology.

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. CWDL 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.

The remainder of this 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. Section 3 introduces the data sources used and presents an overview of their characteristics. The model and estimation results of the production function are explained in Sect. 4. In Sect. 5, I decompose the productivity growth factors. Section 6 provides additional analyses on the

[1] 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. At present, 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%.

[2] 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".

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

[4] 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.

particular focus on first-mover roles and new construction furnace characteristics and shows suggestive evidence of the government's policy role. 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[5] 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.[6] 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 Fig. 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.[7] 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.

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 steel scrap. In this process, impurities are removed, and metallic elements are added to adjust the composition to meet the various requirements of final products.[8] 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[9] in refining time and the amounts of inputs required for operation. A BOF furnace can refine steel in one-fourth to one-fifth time of 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.[10]

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

[6] This section is mainly based on three reference documents: the "History of Oxygen Steelmaking Process in Japan" by Iron and Steel Institute of Japan (1982) describes the history of the BOF's introduction, improvement, and diffusion, "A Decade of Steel History" by Japan Iron and Steel Federation (1969, 1981) that summarizes the history of the Japanese steel industry by decade; 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.

[7] The export value also increased from 220 million yen to 2.30 billion yen.

[8] 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 and consists of a series of manufacturing processes, and the refining process is one of the manufacturing processes. A BOF is a type of equipment/technology used in the refining process, and the refining process consists of several BOFs.

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

[10] 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 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.

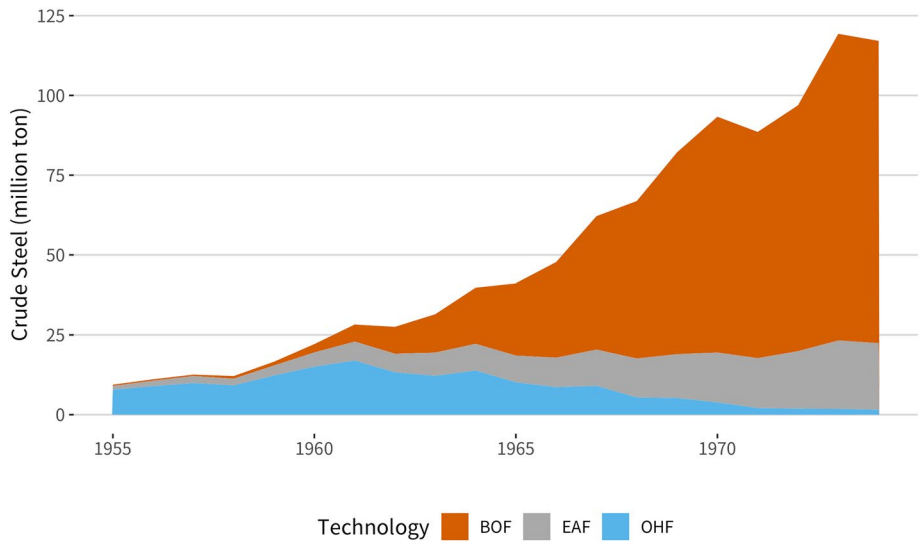

Fig. 1 Crude steel production in Japan (by technology). Data source: "Yearbook of Iron and Steel Statistics". (Japan Iron and Steel Federation 1955–1968b). Crude steel production on the vertical axis is in millions of tons. See footnote 10 for why the electric arc furnace (EAF) are not included in the analysis

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 different foreign companies and competed to be the first to introduce BOF technology in Japan. In the course of negotiations, Yawata Steel was offered a per-ton payment contract, while NKK was offered a lump-sum payment contract.[11] MITI heard from them about the negotiation situation intervened and assigned NKK to be the licensed contractor representing all Japanese steelmakers. Other steel firms 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, tariff exemptions to import equipment for BOF operation, and making the construction of the BOF eligible for World Bank financing.

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 Yawata Steel which is the largest steelmaking company in Japan and one of the first-mover

[11] The lump-sum payment contract was based on the assumption of 12 million tons of crude steel production, but in fact, Japanese BOF crude steel production increased to 42 million tons in 1967.

pioneering companies. Some of the improved technologies developed in Japan were exported overseas and became world standards.[12] 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. Initially, BOF was considered inferior to OHF in quality except for sheet products. However, Japanese steelmaking firms' research effort had expanded the range of products to almost all products while yielding the same quality as OHF in the mid-1960s. Efforts by Japanese steel firms to improve BOF technology likely increased the whole industry's productivity and applicability of the BOF technology.

The fourth factor is operational knowledge sharing among firms, especially from first-mover firms who adopted BOF earlier, Yawata Steel and NKK. First-movers shared their operational knowledge with latecomers in various ways. According to Nakamura and Ohashi (2012a), Yawata Steel freely disclosed information on improved technologies they invented. Additionally, latecomer firms' engineers could visit first-movers' steelworks and receive technical advice on BOF operation from first-movers' engineers. 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.

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 Data source and definition of variables

The primary data source is the *"Reference Material on Steel Making"* (Japan Iron and Steel Federation 1955–1968), 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 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[13,14]

[12] One of the most prominent improved technologies is the OG system (Oxygen converter Gas recovery system), which ultimately would be used in 60% of the world's BOFs.

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

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

4. Intermediate inputs: Pig iron and steel/iron scrap[15]
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"* (Japan Iron and Steel Federation 1955–1968a), which contains the prices of crude steel, pig iron, and scrap. The second is the *"Yearbook of Petroleum Statistics"* (Ministry of International Trade and Industry 1955–1968b), which includes heavy oil prices.[16] The last is the *"Annual Report on Energy"* (Ministry of International Trade and Industry 1955–1968a), 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.[17] Furthermore, I multiply the average working hours per worker.[18]

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 a BOF (Table 1) and an OHF (Table 2), I find that a BOF furnace produces over five times as much as an OHF. For a more detailed comparison, crude steel production per furnace capacity and per worker is shown in Fig. 5 in Appendix, and energy use per ton of crude steel is shown in Fig. 6 in Appendix. The production per furnace capacity is seven times higher for a BOF than an OHF, and the production per worker is five times higher for a BOF than for an OHF. 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 a BOF is low, 2/3 and 1/100, respectively, compared to an OHF. A BOF can produce more crude steel with less capacity (capital), labor, and energy input than an OHF. As mentioned in Sect. 2, the BOF technology appears to have operational advantages over the OHF. Based on this section's observational findings, the next section will construct a structural production function model and estimate it.

[15] 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.

[16] 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.

[17] 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.

[18] The average working hours per worker are reported in the 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.

Table 1 Descriptive statistics: BOF

	BOF ($N = 256$)			
	Mean	**SD**	**Min**	**Max**
Production				
Crude steel (kt)	523.2	326.0	5.1	1648.3
Capital				
Capacity (t/ch.)	73	38	30	180
Labor				
No. workers (pers.)	96	40	13	197
Energy				
Electricity (MWh)	9.4	12.7	0.1	80.7
Heavy oil (kℓ)	0.2	0.4	0	2.0
Material				
Pig iron (kt)	457.4	285.4	0	1387.5
Scrap (kt)	109.3	77.1	1.1	424.3

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")

Table 2 Descriptive statistics: OHF

	OHF ($N = 1286$)			
	Mean	**SD**	**Min**	**Max**
Production				
Crude steel (kt)	92.6	57.9	1.4	326.7
Capital				
Capacity (t/ch.)	73	38	30	180
Labor				
No. workers (pers.)	96	40	13	197
Energy				
Electricity (MWh)	2.5	2.2	0	18.9
Heavy oil (kℓ)	5.2	3.0	0	21.4
Material				
Pig iron (kt)	63.4	48.4	0	253.6
Scrap (kt)	38.9	22.3	0	134.8

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")

4 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 $\psi \in \{\text{OHF}, \text{BOF}\}$ be a technology indicator. A panel composed of furnace $i = 1, \ldots, N$, over periods $t = 1, \ldots, T$, 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:

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

where productivity $\omega_{\psi,\mathrm{it}}$ 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.

4.1 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, hereafter ACF).

4.1.1 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:

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

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

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

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

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

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

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

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}:

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

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:

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

Then, the conditional moment condition (10) is:

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

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

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

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

4.1.2 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:

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

The cutoff rule differs across technologies.

Then the productivity process Eq. (8) must be rewritten as:

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

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

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

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:

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

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

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

4.2 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. 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	0.343 (0.409)	0.445*** (0.049)	0.343*** (0.151)	0.362** (0.199)
Labor	0.575*** (0.097)	0.590*** (0.049)	0.574*** (0.082)	0.565*** (0.092)
Capital × BOF		0.742*** (0.292)	0.836*** (0.212)	0.849*** (0.321)
Labor × BOF		− 0.396* (0.214)	− 0.417*** (0.099)	− 0.437*** (0.113)
ϕ function	Polynomial	Polynomial	Polynomial	Kernel
Selection correction	Yes		Yes	Yes
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, "Yes" 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 approximately 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 capital-augmenting technological progress.

Although CWDL 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 the old function. One possible explanation for this difference is that 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 over 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-year idiosyncratic effects.

Figure 2 illustrates the annual trends in average productivity for each technology (see detailed numbers in Table 8 in Appendix). As BOFs expand their share, the BOF

Table 4 BOF advantage in productivity

	Productivity ω			
	(1)	(2)	(3)	(4)
BOF dummy	1.713*** (0.028)	2.172*** (0.538)	2.281*** (0.029)	1.625*** (0.027)
Fixed effect				
Furnace	Yes			Yes
Firm × year		Yes		Yes
Plant × year			Yes	Yes
N	1505	1505	1505	1505
Adj. R^2	0.817	0.855	0.943	0.894

Standard errors in parentheses. Asterisks indicate the significance level; *at 10 percent, **at 5 percent, and ***at 1 percent

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

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 Fig. 2 of this study are similar. In both studies' results, BOF productivity multiplies, and OHF productivity does not change substantially.[19] 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.

5 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.

5.1 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

[19] 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 to be compared with caution.

growth or reallocation. Furthermore, to delve deeper into the effect of technology—the main focus of this study—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.

5.1.1 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.[20]

Method 1: industry-wide (Olley–Pakes) decomposition.

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

In Eq. (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 $s_t(\psi)$. 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.

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

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 $\overline{\Omega}_t = \frac{1}{2}\sum_\psi \Omega_t(\psi)$.[21] Then, the between-technology decomposition is as follows.

[20] I follow CWDL regarding the notations and definitions.

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

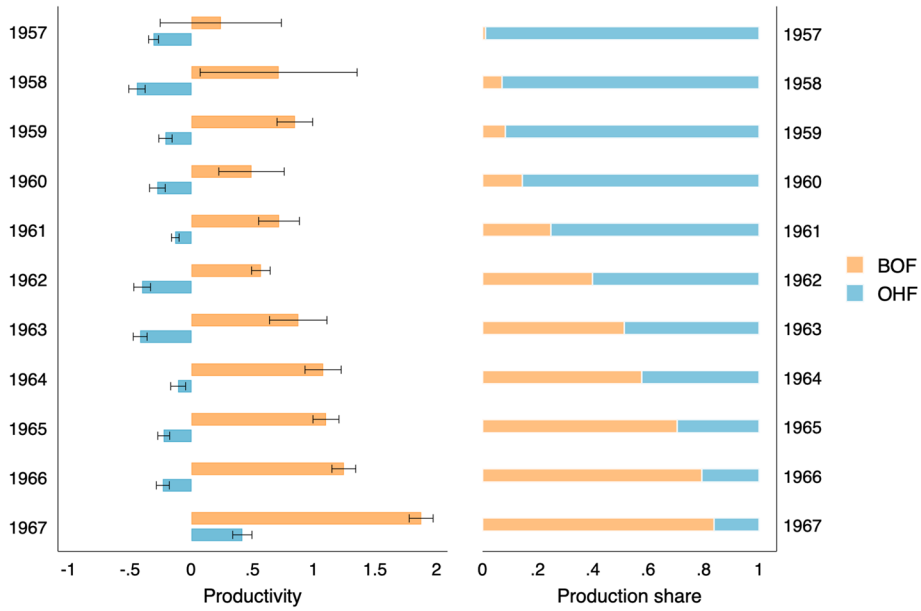

Fig. 2 Productivity trend by technology. In the left graph, the bars represent the productivity levels, and the lines represent the 95% confidence intervals. Productivity is demeaned by industry total sample averages (not technology-specific averages)

Method 3: between-technology decomposition.

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

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

$$\begin{aligned}\bar{\Omega}_t &= \frac{1}{2}\sum_{\psi} \Omega_t(\psi) = \frac{1}{2}\sum_{\psi}\sum_{i \in \psi} s_{it}(\psi)\omega_{it} \\ \Leftrightarrow \bar{\Omega}_t &= \frac{1}{2}\sum_{\psi \in \text{BOF,OHF}} \Big(\bar{\omega}_t(\psi) + \Gamma_t^{\text{OP}}(\psi)\Big).\end{aligned} \tag{20}$$

By substituting Eq. (20) into Eq. (19),

$$\Omega_t = \frac{1}{2}\sum_{\psi \in \text{BOF,OHF}} \left[\underbrace{\overline{\omega}_t(\psi)}_{\text{Operation improvement}} + \underbrace{\Gamma_t^{\text{OP}}(\psi)}_{\text{Within-reallocation}}\right] + \underbrace{\Gamma_t^B}_{\text{Between-reallocation}} . \tag{21}$$

Table 5 Static decomposition

$\Delta\Omega_t$	1.872	
Olley–Pakes		
Operational improvement: $\overline{\omega}_t$	1.297 (69.3%)	
Reallocation effect: Γ_t^{OP}	0.575 (30.7%)	
Between-technology		
Operational improvement: $\overline{\Omega}_t$	1.165 (62.2%)	
Reallocation effect: Γ_t^{B}	0.707 (37.8%)	
Within-technology	**BOF**	**OHF**
Total growth	1.586	0.744
Operational improvement: $\overline{\omega}_t(\psi)$	1.635 (103.1%)	0.725 (97.4%)
Reallocation effect: $\Gamma_t^{OP}(\psi)$	− 0.050 (− 3.1%)	0.019 (2.6%)

The share of each factor in productivity change is in parentheses

Using Eq. (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.

5.1.2 Static decomposition: results

The static results for Olley–Pakes, between-technology, and within-technology decomposition are shown in Table 5. Based on the Olley–Pakes and the between-technology decomposition, the operational improvement effects account for approximately 62% to 69% 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 3 shows the decomposition result for operational improvement and the within-reallocation effects by technology and the between-technology reallocation effect, as defined in Eq. (21). The factor with the most outstanding contribution is the operational improvement of the BOF, which accounts for 44% of aggregate productivity growth. The second-largest factor is the between-technology reallocation, which accounts for 38% of productivity growth. The production reallocation from OHF to BOF had an essential impact on the increase in aggregate productivity.

5.2 Dynamic decomposition

The static decomposition results revealed that reallocation effects are an important factor that accounts for nearly 30 to 40% 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.

5.2.1 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[22]

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

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.[23]

Dynamic decomposition is conducted both within- and between-technology as in the static decomposition. Analogous to Eq. (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:

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

Because the terms within brackets is the exactly the form of the dynamic decomposition formula (22),

[22] In the dynamic decomposition accounting for entry and exit, I use the method suggested by Davis et al. (1996) and employed in CWDL, among others.

[23] 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, $\sum_{i\in\mathcal{N}} s_{it}(\omega_{it} - \bar{\omega})$, 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.

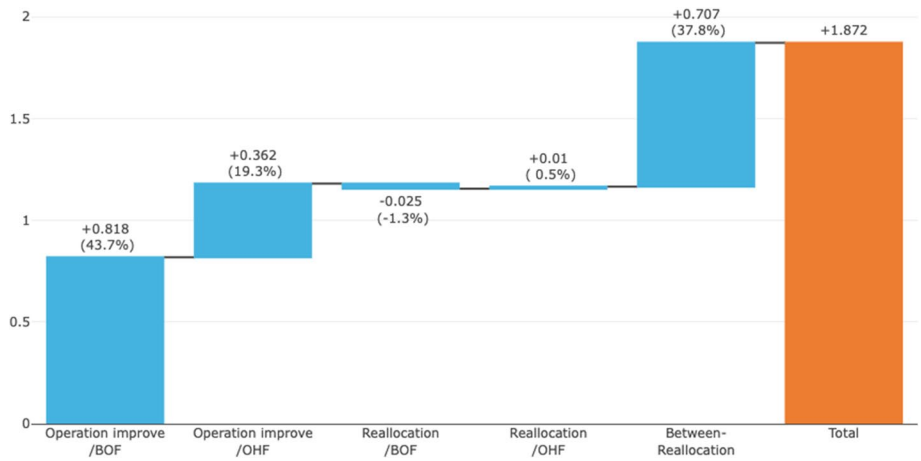

Fig. 3 Static decomposition. The figures in parentheses show the share of each factor in aggregate productivity growth. As Eq. (21) shows, the contribution of within-technology decomposition terms to the aggregate productivity growth is calculated using half the value in Table 5

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

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.

5.2.2 Dynamic decomposition: results

Applying Eq. (22) to all furnaces pooled and by technology, Table 6 shows the dynamic decomposition results. Compared to the static decomposition results, the dynamic

Table 6 Dynamic decomposition

$\Delta\Omega_t$	1.872	
Across all furnace		
Operational improvement	0.979 (52.3%)	
Reallocation	0.407 (21.7%)	
Entry–exit premium	0.487 (26.0%)	
Technology-specific		
Within-technology part	1.246 (66.6%)	
Between-reallocation	0.707 (37.8%)	
Within-technology	**BOF**	**OHF**
Total growth	1.586 (42.4%)	0.744 (19.9%)
Operational improvement	2.071 (55.3%)	0.422 (11.3%)
Reallocation	− 1.621 (− 43.3%)	0.252 (6.7%)
Entry–exit premium	1.136 (30.4%)	0.070 (1.9%)

Share of each factor in productivity change is in parentheses

factor—the entry–exit premium—represents about one-third of the aggregate productivity growth. This result suggests that the construction of new furnaces is a critical 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 4 displays the technology-specific decomposition result for operational improvement and within-reallocation effects by technology, between-technology reallocation, and entry–exit effects defined in Eq. (23). Regarding the technology-specific decomposition, the BOF operational improvement has the highest contribution to aggregate productivity growth (a 55% share). The between-technology reallocation to existing and newly constructed furnaces combined accounts for a 70% 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 effect with a −43% contribution.

6 Discussion: productivity growth and policies

The decomposition analysis in the previous section revealed that operational improvement and reallocation to the new technology, including construction of new furnaces, both largely contribute to productivity growth at the cost of allocation efficiency within the new technology. Operational improvement is investigated in the previous literature, especially Nakamura and Ohashi (2012a), from the perspective of user-invented improved technology, so-called re-invention. Nakamura and Ohashi (2012a) focus on the OG system and the multi-hole lance that Yawata Steel invented. They utilize introduction data of these two inventions to steelworks and find that these two re-inventions account for 30% of productivity growth.[24] Therefore, this subsection will conduct additional quantitative analysis and discuss factors that promote between-technology reallocation and worsened within-technology reallocation.

The Japanese government facilitated the introduction of the BOF, the between-technology reallocation by policies described in Sect. 2. First, industry-wide license sharing and BOF operational knowledge sharing by first-movers made it easier for latecomer firms to adopt BOF technology. Thus, it seems likely that firms constructed BOF furnaces regardless of whether they were experienced first-mover firms. Moreover, the low license fee and tax reduction policies decreased BOF construction costs and lowered the productivity threshold to enter.

Table 7 reports the results of probit regression analyses of the difference in the probability of building new BOF furnace(s) between first-movers and others. There is no significant difference in new BOF construction probability between first-movers and others when controlling for the size of the firm and plant. [25] Moreover, a firm's BOF operating experience in years has no significant effect on BOF furnace construction. Thus, it is suggested that the

[24] These results must be interpreted with caution because their analysis unit is plant-level, and the production function specification is different.

[25] "Because the year fixed effectis included, I use a bias collection method for the probit regression (see Cruz-Gonzalez et al. 2017).

Table 7 New furnace construction probability

	Construct new furnace	
	(1)	(2)
First-movers	0.479 (0.298)	0.263 (0.321)
Firm crude steel production	0.165*** (0.059)	0.013 (0.081)
Plant crude steel production		0.296*** (0.101)
BOF experience	0.009 (0.047)	0.066 (0.054)
Year fixed effect	Yes	Yes
Observations	243	243

Standard errors in parentheses. Asterisks indicate the significance level: *at 10 percent, **at 5 percent, and ***at 1 percent

Analysis is at the plant level. The dependent variable is a dummy variable that takes value one if a plant constructed new furnace(s)

First-movers are Yawata and NKK, and crude steel productions are in 1 million tons

government policies that facilitated all firms' access to BOF technology and knowledge sharing among steelmaking firms lowered the barrier to introducing BOF. Furthermore, Table 9 in Appendix shows that new furnaces' productivity is lower within BOF furnaces. Nakamura and Ohashi (2008) noted that there was a learning-by-doing effect in BOF furnace operation after its adoption. The government's policy of lowering BOF construction costs, which allowed firms to build new furnaces even with low initial productivity, is likely to have given steelmaking firms room for learning-by-doing. Although this situation worsened within-BOF production reallocation, steelmaking firms could smoothly transition to the new BOF technology and enjoy a high productivity growth of BOF.

7 Conclusion

This paper examines the impact of new technology on productivity growth when 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: (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 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 70% and 55% 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. Conversely, within-BOF allocative efficiency worsened by approximately 43% of productivity change. Government policies at that time might be responsible for facilitating new technology furnace construction regardless of whether a firm is a first-mover. While within the new technology allocation efficiency temporarily declined due to the construction of lower productivity new furnaces, steelmaking firms enjoyed new technology productivity improvement, which outweighed the within-reallocation effect.

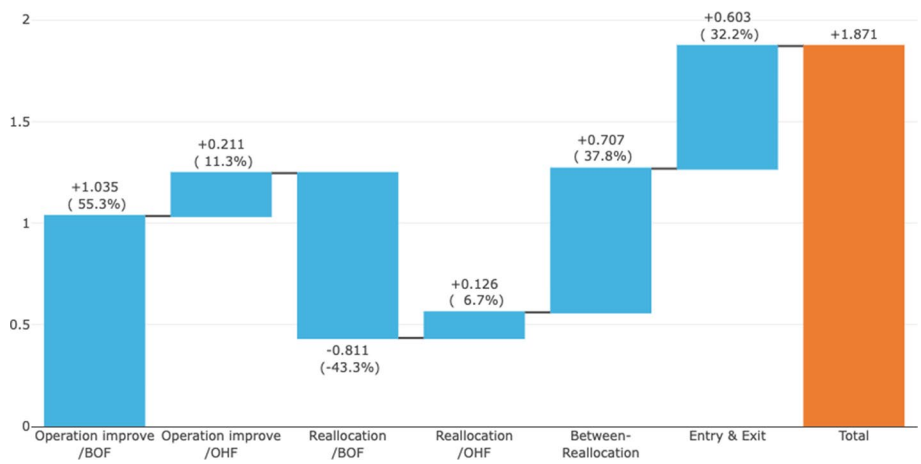

Fig. 4 Dynamic decomposition: each factor contribution. The figures in parentheses show the share of each factor in aggregate productivity growth, using the results in Table 6. As Eq. (23) shows, the contribution of the within-technology decomposition terms to the aggregate productivity growth is calculated using half the value in Table 6

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. A structural estimation considering plants' new furnace construction and divestment decisions on each technology will be fruitful to quantify how much faster firms introduced the BOF furnaces than they would have in the absence of various government policies such as license sharing, tax exemption, and so forth.

Appendix

This appendix section shows additional tables (Tables 8, 9) and figures (Figs. 5, 6).

Table 8 Productivity change by technology

	BOF		OHF		(BOF) − (OHF)
	Productivity	**No.**	**Productivity**	**No.**	**Productivity**
1957	0.239 (0.355)	2	− 0.310 (0.227)	121	+ 0.549 [0.277, 0.871]
1958	0.711 (0.460)	2	− 0.445 (0.369)	117	+ 1.156 [0.635, 1.678]
1959	0.844 (0.165)	5	− 0.212 (0.297)	115	+ 1.056 [0.790, 1.322]
1960	0.490 (0.428)	10	− 0.278 (0.369)	128	+ 0.768 [0.525, 1.011]
1961	0.714 (0.338)	16	− 0.132 (0.180)	127	+ 0.846 [0.740, 0.953]
1962	0.566 (0.189)	24	− 0.403 (0.392)	126	+ 0.969 [0.807, 1.131]
1963	0.871 (0.630)	28	− 0.419 (0.320)	122	+ 1.290 [1.126, 1.454]
1964	1.074 (0.418)	31	− 0.109 (0.332)	116	+ 1.183 [1.042, 1.323]
1965	1.098 (0.344)	41	− 0.227 (0.257)	109	+ 1.325 [1.222, 1.427]
1966	1.243 (0.328)	44	− 0.234 (0.252)	88	+ 1.477 [1.375, 1.579]
1967	1.875 (0.360)	53	0.415 (0.357)	80	+ 1.460 [1.334, 1.585]
Average	1.144 (0.579)	–	− 0.234 (0.370)	–	+ 1.378 [1.322, 1.424]

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

Table 9 New furnace productivity

	Productivity ω		
	(1)	(2)	(3)
New furnace	−0.379*** (0.056)	−0.212*** (0.048)	−0.248*** (0.058)
Year FE	Yes	Yes	Yes
Firm FE	Yes		
Plant FE		Yes	
Furnace FE			Yes
Observations	256	256	247

Standard errors in parentheses. Standard errors are clustered at the firm level. Asterisks indicate the significance level: *at 10 percent, **at 5 percent, and ***at 1 percent

New furnace takes value one if constructed in that year. First-movers are Yawata and NKK

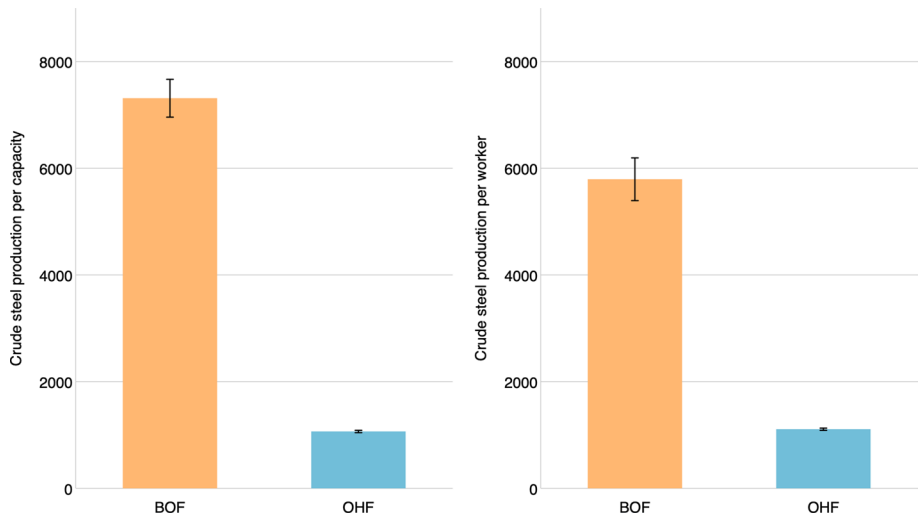

Fig. 5 Crude steel production, per worker and per capacity. The graphs show crude steel production per furnace capacity 1 m^3 (=capital productivity) and per worker (labor productivity). Units are tons. Lines are confidence intervals

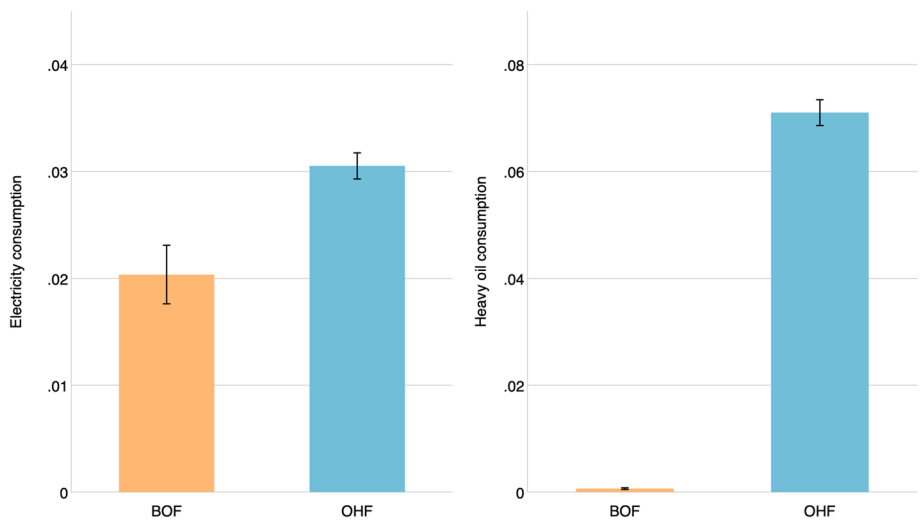

Fig. 6 Energy consumption per crude steel production (electricity and heavy oil). The graphs show electricity and heavy oil consumption per crude steel production. Units are kWh/t and ℓ/t, respectively. Lines are confidence intervals

Abbreviations

BOF	Basic oxygen furnace
OHF	Open-hearth furnace
EAF	Electric arc furnace
OG system	Oxygen converter gas recovery system
MITI	The Ministry of International Trade and Industry (Japan)
NKK	Nihon Ko-Kan
CWDL	Collard-Wexler and De Loecker (2015)
ACF	Ackerberg et al. (2015)

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Author contributions
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Availability of data and materials
The datasets used and analyzed during the current study are available from the author upon reasonable request.

Declarations

Competing interests
The authors declare that they have no competing interests.

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