CIRJE-F-813

Effects of Re-invention on Industry Growth and Productivity: Evidence from Steel Refining Technology in Japan, 1957-68

Tsuyoshi Nakamura
Tokyo Keizai Univeristy

Hiroshi Ohashi
University of Tokyo

August 2011

Effects of Re-invention on Industry Growth and Productivity: Evidence from Steel Refining Technology in Japan, 1957-68 *

Tsuyoshi Nakamura † Hiroshi Ohashi ‡

Abstract

This paper examines the economic impact of re-invention — the degree to which an innovation is modified by user — on industry growth and productivity. The paper focuses on two re-inventions made by a Japanese steel company; these inventions improved the productive efficiency of Austrian-made refining technology, namely, basic oxygen furnace (BOF). Results obtained from the plant-level production-function estimation indicate that re-inventions account for approximately 30 percent of the total factor productivity of the BOF, substantially promoting the dissemination of the BOF technology. Our simulation analysis indeed reveals that re-inventions contributed to steel output growth by about 14 percent. This paper also documents that innovating companies played the role of a "lead user" in developing and disseminating their re-invented technologies.

Keywords: re-invention; lead user; total factor productivity; steel

JEL: O31, O33, D24, L61

1 Introduction

The history of major technologies is characterized by occasional major inventions followed by a wave of improvements (Nelson and Winter, 1982: 257). A long process of improvements, often called re-invention, is required in order for such technologies to successfully prevail in the economy.[1] Among many examples, the studies of Enos (1962) on petroleum refining and those of Hollander (1965) on rayon textile illustrate that re-invention tends to contribute just as much to technological progress as the original technological breakthrough does. While the importance of re-invention has been featured in a number of anecdotes, there is a severe paucity of empirical research that measures the magnitude of the impact of re-invention on the productivity and profitability. The purpose of this paper is to go some way towards redressing that balance by offering empirical evidence in the effect of re-invention on industry growth and productivity.

*We thank Hiroyuki Odagiri, Arnold Picot, Eric von-Hippel and seminar and conference participants at the Japan Economic Association meetings, LMU and the HBS-MIT User Innovation Workshop for helpful comments.

†Department of Economics, Tokyo Keizai Univeristy.

‡(Corresponding Author): Department of Economics, University of Tokyo. 7-3-1 Hongo, Tokyo, Japan. Phone: +81-3-5841-5511. ohashi@e.u-tokyo.ac.jp.

[1] The process of technological improvements is sometimes called by other terms, including follow-on innovations, accumulated improvements, or incremental innovations. In this paper, we collectively call re-invention, following Rogers (2003).

Using a unique example from the Japanese steel industry, this paper quantitatively assesses the role of re-invention in technological improvements. After the late 1950s, steel manufacturers around the world gradually upgraded their refining furnace technology, shifting from the conventional open-hearth furnace (hereafter OHF) to the Austrian-made basic oxygen furnace (BOF). While the introduction of the BOF was praised as "unquestionably one of the greatest technological breakthroughs in the steel industry during the twentieth century" (Hogan, 1971: 1543), several technical problems had to be resolved before the BOF technology was widely implemented. Two major problems were associated with slag slopping and exhaust gas emission. Developing improved devices to cope with these problems was imperative to ensure steel production that was cost-efficient and precise in terms of specifications and to minimize the negative environmental effects of steel manufacturing.

In response to the technical difficulties, two innovative improvements were introduced in the BOF in 1962, namely, multi-hole lance (hereafter MHL) and oxygen converter gas recovery (hereafter OG) systems: The MHL enabled substantial reduction in the frequency of slag slopping, and the OG system provided a method to recycle gas and heat generated from the steel refining stage. Interestingly, these improvements were introduced not by the Austrian, inventor of the BOF, but by a Japanese, importer and user of the technology. The two user-developed re-inventions successfully improved the productive efficiency of the BOF use, and gained wide acceptance among not only domestic but also foreign steel companies. For example, by the late 1970s, firms such as U.S. Steel, Bethlehem, Armco, and Inland produced steel under the licenses of MHL and OG systems that were obtained from Japan.

The interest of this paper, MHL and OG, is considered as a typical example of re-invention, as they fit into three common features of re-invention summarized by Rogers (2003): re-invention (i) occurs at the implementation stage for many innovations and for many adopters; (ii) leads to a faster rate of adoption of an innovation; and (iii) leads to a higher degree of sustainability (i.e., the degree to which an innovation continues to be used over time after a diffusion program ends) of an invention. Both MHL and OG were improvements occured in the course of using BOF by Japanese steel companies. The introduction of these two improvements strenghthened the advantage of BOF over the old technology, OHF. As shown in Figure 1, the share of BOF surpassed that of OHF shortly after the apperance of MHL and OG, and steadily increased up to the level of 80% in 1970.

The two technological improvements are regarded as successful re-inventions that helped promote the BOF diffusion, leading to the remarkable growth of the Japanese steel industry in the 1950s and 60s. They have been served as "two most important generally applicable improvements in BOF hardware" (Lynn, 1982: 34), and thus the episode of MHL and OG is reasonably considered as supplying a notable example where re-inventions play an important role in industrial develpment.

To assess the contribution of re-inventions on industry growth and productivity, we employ a unique plant-level data set that covers the inputs and outputs of the BOF and the installation timing and usage intensity of the innovations. The data permit estimations of the production function based on the BOF technology and of the changes in productivity, profitability, and output growth both before and after the adoption of re-invented technologies. Our estimation results for total factor productivity (hereafter TFP) indicate that these re-inventions contributed to approximately 30 percent of the BOF productivity growth. Thus, the advent of the re-inventions developed by users facilitated the dissemination of BOF technology, thereby promoting the growth of the Japanese steel industry, as observed in Figure 1. Based on the estimation results, this paper substantiates the possibility that had the re-inventions of the MHL and OG systems not been developed, the output level of the Japanese steel industry in the 1960s would be more than ten percent lower than what we saw in the data.

The re-invention in principle occurs on the sides of both producers and users. As surveyed in Rogers (2003), a number of cases exist where users play a role in re-invention in the literature of process innovation. Studies on innovating users show that such re-inventions are likely to be concentrated among the "lead users." According to the definition proposed in von Hippel (1986), lead users are ahead of the majority of users with respect to an important market trend and that they expect to secure large benefits by proposing solutions to their leading edge needs. A close observation of re-inventions of the MHL and OG systems as documented in industry trade journals reveals that a company named Yawata appeared to play the role of a lead-user. As the largest steel producing firm in Japan, Yawata actively sought solutions for the technical problems of slag slopping and exhaust gas emissions resulting from BOF use. Indeed, Yawata was the first to adopt the BOF in Japan and produced the highest share of output through BOF use during the study period; thus, it had the most number of incentives to improve the productivity of its BOF. Upon the successful development of its MHL and OG systems, Yawata freely shared the details of its innovations with other Japanese steel manufacturers, providing additional momentum to the dissemination of re-invented technologies.[2] Our simulation analysis, based on the production function estimation, reveals that the profits Yawata secured from its re-inventions of the MHL and OG systems would have far exceeded those of the company with the second highest profits.

The rest of the paper is organized as follows. Section 2 provides an overview of the Japanese steel market after the World War II. It mainly describes the two technological improvements — the MHL and the OG systems — developed by a user of the BOF technology. Further, it illustrates that the innovating user, i.e., Yawata, exhibited the characteristics of a lead user and that it freely revealed the technical details and performance of the re-inventions to other Japanese manufacturers. Section 3 delineates the framework employed in estimating the productivity of re-invented technologies. Our plant-level panel data set allows us to address the issues of endogeneity and serial correlation in productivity measurement. The estimates indicate that re-inventions accounted for approximately 30 percent of the growth in steel-making productivity. Using the obtained estimates, this section also examines the steel output, considering a hypothetical situation in which no Japanese steel plants adopted re-invented technologies during the study period from 1957 to 1968. The difference between the actual and simulated outputs is considered as the contribution made by re-inventions. Finally, in Section 3, we calculate the amount of profits accrued by Japanese steel companies via re-inventions. We discover that re-inventions did not benefit to all companies uniformly; instead, it was the inventing company that benefitted the most. Section 4 provides the concluding remarks, followed by data appendix.

[2] While it was freely disclosed in the domestic market, Yawata licensed its re-invented technologies to foreign competitors under royalty agreemnents.

2 Re-invention in Steel Refining Technology

Japan experienced a remarkable growth in steel production shortly after World War II. Figure 1 illustrates that production in this industry expanded more than fourfold between the 1950s and 1960s. This not only satisfied the rapidly growing domestic demand but also stimulated steel exports, which grew at over 20 percent annually, raising Japan to the status of the world's largest steel exporter in 1969.

A large portion of Japanese steel production in the 1950s and 1960s was accounted for by integrated steel manufacturers. These manufacturers processed raw materials (iron ore and coking coal) into pig iron in a blast furnace. Pig iron is subsequently converted into crude steel in another furnace by the removal of carbon and other elements. The prevalent technology used in this second or "refining" stage was that of OHF, wherein air is blown from the bottom of a brick-lined steel shell through molten pig iron. The air increases the temperature of the pig iron and oxidizes the carbon in it. In the late 1950s, the OHF began to rapidly lose ground to the BOF. Invented by an Austrian firm in 1952, the BOF technology involved the passage of oxygen for the oxidization of the iron and was expected to refine molten iron and scrap charge into steel in approximately 45 minutes—a sharp decrease from the 6 hours normally required by the OHF.

However, in achieving the full technical and economic potential of the Austrian-made technology, global steelmakers were confronted with two technical problems, namely those associated with (a) slag slopping and (b) exhaust gas emissions. During the refining operation, slag foam was created to improve the BOF performance. Problem (a) arose when the foam level exceeded the height of the vessel and overflowed, resulting in severe dust emissions and yield reduction. Furthermore, steel production needed to be discontinued to clean the area below the vessel and the vessel mouth. These issues motivated a search for methods to maintain a suitable foam volume, while preventing the occurrence of slopping. Problem (b) emerged when more stringent environmental standards were introduced in the late 1950s. The BOF was known to discharge the most significant level of emissions in the steel-making process. Thus, better air cleaning technology for controlling emissions was regarded as crucial for the dissemination of the BOF technology. It was primarily due to problems (a) and (b) that foreign firms, some of which had implemented the BOF earlier than did the Japanese, did not extensively adopt the technology.

These technical difficulties were resolved by two re-inventions introduced in 1962. One of them was the MHL, which adds more oxygen nozzles in the BOF lance to prevent slag slopping. The BOF lance is a pipe that blows oxygen into molten pig iron in the furnace, and the configuration change in the lance of steel companies allows oxygen to be blown at lower velocities and thus reduces splashing in the BOF. The adoption of the MHL resulted in increased steel-making yield and improved refractory life; thus, the innovation helped facilitate the scaling up of BOF's in the mid-1960s. To solve the problem of exhaust emissions, the OG system was developed to recover gases and fumes released during the BOF steel-making process. By recycling waste gas, the OG system not only prevented pollution but also reduced energy usage. Both the MHL and the OG systems were believed to enable steel companies to achieve higher production rates with lower costs. In Section 3, we will estimate the extent to which these re-inventions improved the productivity of the steel refining process.

The MHL and OG systems were simultaneously introduced in Japan in 1962, five years after the BOF was introduced in Japan. Interestingly, these systems were not created by the inventor of the BOF but by a Japanese company, namely, Yawata, which was an importer and user of the technology. As shown in the right column of Table 1, Yawata produced the largest amount of steel using the BOF technology, accounting for more than 20 percent of the total output in Japan. Hence, it is reasonable to consider that Yawata was the most incentivized to improve the efficiency of the BOF operation. Trade journals, including the Iron and Steel Institute of Japan (1982), revealed that the MHL and OG systems were the outcome of considerable experimental efforts that could only be conducted by a company with sufficient familiarity and experience in using the BOF technology. During the period of five years from 1957 to 1962, Yawata learned through trials and errors the most efficient configurations to minimize both slag slopping and energy usage.

Another interesting observation is that Yawata freely disclosed pertinent information concerning the technical details and the performance of their re-inventions to domestic competitors. Thus, competing firms could liberally use the released information while installing systems developed by Yawata's innovative technologies. Yawata, however, did not reveal its re-inventions to foreign competitors free of charge; instead, it licensed its re-inventions under royalty agreements with them. Although it is beyond the scope of this paper to consider as to why Yawata was so altruistic as to domestically supply such a public good, this type of free information-disseminating behavior has been frequently observed in other innovations, for example, blast furnace technology of Cleveland in the U.K. (Allen, 1983) and the Cornish pumping engine (Nuvolari, 2004).[3] In all likelihood, Yawata's voluntary knowledge spillovers helped disseminate its re-invented technologies. Table 1 presents the diffusion processes of re-inventions across plants. While both re-invented technologies were first deployed in the same year, i.e., 1962, the diffusion paths diverged thereafter; the MHL proliferated fast and achieved full penetration across firms in 1965, when the OG system was adopted by half the existing plants. The diffusion rates differed, because it was much easier for a plant to replace a conventional BOF lance by the MHL, than to build gas recycling facility next to its furnace. The different diffusion rates observed in the table allow us to separately identify the effects of the respective re-inventions on industry growth and productivity, as discussed in Section 3.

The technological improvements conducted by Yawata received considerable attention from foreign steel-makers as well. Although Yawata had licensed its re-invented technologies for royalty fees, the re-inventions were highly appreciated abroad. For example, beginning with West Germany in 1963, the OG system was adopted by more than 60 percent of the foreign steel manufacturers by the mid-1970s. Eventually, the royalties obtained from this technology by the Japanese proved to be more than the amount they had paid the Austrian company to obtain license rights for the BOF. In the next section, we quantitatively assess the extent to which re-inventions contributed to the Japanese steel market in the 1950s and 1960s.

3 Economic Impacts of Re-inventions

This section, which comprises two subsections, analyzes the economic effects of re-inventions on industry growth. Section 3.1 presents the method used to estimate the productivity of re-inventions in the steel refining process, namely the MHL and OG systems. To achieve this, we require estimates of the production function that describes the steel refining process of the BOF. The estimation results, also presented in this section, indicate that re-inventions accounted for approximately 30 percent of the TFP increase in the BOF

[3] Lerner and Tirole (2002) attempt to explain this behavior in the context of open source software development.

process. Using the obtained estimates, Section 3.2 examines the steel output considering a hypothetical situation in which Japanese steel companies did not adopt the MHL and OG systems. We find that re-inventions indeed contributed to the expanded steel production, and without them, the output would have been 14 percent smaller than the actual output. However, the re-inventions did not lead to uniform benefits for all Japanese companies. In fact, our simulation result indicates that the profits earned by the innovating company, Yawata, were at least 30 percent higher than those earned by other companies.

3.1 Econometric Analysis of Production Function

3.1.1 Estimation Model

In this subsection, we empirically analyze the productivity of re-inventions, namely, the MHL and OG systems, in steel production. For this, we first estimate the production function that describes the BOF steel refining process. The BOF produces crude steel of homogenous quality, regardless of whether the MHL or the OG system is installed. Our econometric model of the production function assumes the following Cobb-Douglas form (all variables are in logarithmic form). The summary statistics of the variables are shown in Table 2.

$$y_{i,t} = \alpha_{i,t} + \beta_l l_{i,t} + \beta_x x_{i,t} + \beta_k k_{i,t} + \beta_z z_{i,t} + u_{i,t} \tag{1}$$

Several preceding studies use the Cobb-Douglas function in the productivity measurement of the steel industry. For example, Tyler (1979) studies on Brazilian steel, and Satomura (1971) and Nakamura and Ohashi (2008) analyze steel productivity in Japan. Jefferson (1990) employs a flexible functional form to conclude that the assumption of the Cobb-Douglas form cannot be rejected. This paper employs the same functional form used in the literature and provides a new insight on the role of re-invention in the application of Japanese steel industry in the 1957 - 1968 period.

The annual output (in tons) at plant i in year t is denoted by $y_{i,t}$. The production function comprises several input variables. The electricity (in gigawatt hours) and labor (in thousand man hours) inputs are denoted respectively by $l_{i,t}$ and $x_{i,t}$. The capacity size (in tons per charge) is indicated by $k_{i,t}$, and the number of years of the BOF use is denoted by $z_{i,t}$. The latter variable captures two aspects of capital utilization. On one hand, it reflects the experience level, i.e., the extent to which extensive use of a particular furnace type leads to more efficient production. On the other hand, the variable indicates the degree of capital depreciation, as furnace productivity deteriorates with age. The estimated coefficient, β_z, indicates which of the two effects is more dominant in our application. The production function (1) implicitly assumes that, given the value of $k_{i,t}$, the number of BOF's owned by a plant does not affect the production level for plant i in year t. Our estimation results discussed in the next subsection relax this assumption and allow for discontinuity over multiple BOF's in the capacity-size variable.

Since the MHL and OG systems contributed to improving yields and saving energy costs, we include the effect of the re-inventions in the constant term, $\alpha_{i,t}$, as follows.

$$\alpha_{i,t} = \gamma_0 + \gamma_{MHL} \cdot MHL_{i,t} + \gamma_{OG} \cdot OG_{i,t} + \gamma_T \log t \tag{2}$$

in which $MHL_{i,t}$ (or $OG_{i,t}$) indicates the extent to which the MHL (or OG system) was instituted at plant i in year t, as presented in Table 1. Thus, either indicator takes the value in the range between 0 (when none of the BOF furnaces in plant i had adopted the corresponding user innovation) and 1 (when all furnaces at plant i adopted it).[4] The last term in the RHS of (2) is the trend, intended to capture general productivity growth of BOF. While Lynn (1982; 34) points out the prolonged lives of refractories through the bricks used to line the BOF, our data fail to quantify such technical dimension of BOF. The trend term would control for such unmeasured improvements in the furnace technology. Note that the trend term captures the first-order approximation of the diffusion paths of the re-inventions. Since as Table 1 shows, both MHL and OG diffused at accerelated rates, the estimated coefficient of γ_T may understate the real impact of the re-inventions on productivity in the latter half of our study period. The Greek letters, β_l, β_x, β_k, β_z, γ_0, γ_{MHL}, γ_{OG} and γ_T represent the parameters to be estimated.

Notice that $y_{i,t}$ is measured in terms of output quantity and not value added. Many studies use value added, deflated by a common industry deflator, under the implicit assumption that the product market is perfectly competitive. If this assumption is violated and the dispersion in output prices is observed, it is difficult to obtain unbiased estimates of production-function parameters because the deflated sales differ from the actual output (Klette and Griliches, 1996).

Apart from the explanatory variables mentioned in (1) and (2), an important influence on steel production is the plant-level efficiency in production management, which is unobservable and represented by $u_{i,t}$. The presence of this term may create endogeneity in input and technology choices**.**

Endogeneity in input choice arises when producers adjust the amount of inputs (the amounts of labor and electricity in our application) according to their efficiency differences in $u_{i,t}$. A method that fails to account for such correlation would generate biased estimates. Our response to the endogeneity problem is to use plant-specific components in the estimation — $u_{i,t} = \lambda_i + \varepsilon_{i,t}$, where $\varepsilon_{i,t}$ denotes a mean-zero error. The plant fixed component (λ_i) deals with efficiency differences among plants that do not change over time.

It may appear to be restrictive to assume that the plant fixed component is constant over time. However, this assumption appears reasonable with respect to our data and is consistent with the observation that the order of the plant-level production share remained constant during the sample period. Spearman's rank correlation coefficient in terms of the BOF production share is 0.82 at the 99 percent confidence level between 1957 and 1968; moreover, the deviation from perfect correlation is entirely due to plant entry. [5],[6] Furthermore, in the estimation, we use the method proposed by Baltagi and Wu (1999) to control for serial correlation in $\varepsilon_{i,t}$.[7]

[4] We assume that $MHL_{i,t}$ (or $OG_{i,t}$) takes a value equal to the proportion of the furnaces equipped with the MHL (or the OG) systems in plant i in year t. Our estimation results discussed in this section are quantitatively unaltered under the alternative assumption that the variable takes the value of 0.5, when some but not all furnaces in plant i adopted the corresponding re-inventions.

[5] The stability of market share is often observed in other industries in Japan. See Sutton (2005) for details.

[6] An alternative method to control for unobserved productivity is to create a proxy for u_{it} by introducing an input demand equation from outside the production-function framework. A previous version of this paper attempted to apply this method and reports that the infrequency of investment fails to use the Olley and Pakes (1996) method and that the use of material input (pig iron and scrap in our case), as per the idea adopted from Levinsohn and Petrin (2003), generates unreasonable productivity estimates. The Levinsohn-Petrin approach has also been recently criticized by Ackerberg, Caves, and Frazer (2005). Based on these findings in the previous version, this paper does not employ these methods to control for unobserved productivity.

[7] While Arellano and Bond (1991) proposes an alternative method to address serial correlation, the method is known to have

Endogeneity (or selection) in choice of technology choice arises when a firm's decision with regard to the adaptation of re-invented technologies is not random but correlated to the productivity, $u_{i,t}$. The severity of the selection bias depends on the magnitude of the productivity difference between plants that adopt re-invented technologies and those that do not. In theory, two hypotheses exist with regard to the relationship between plant productivity and technology adoption. One is that the more productive plants are likelier to adopt a new technology. For example, Caselli (1999) argues that skilled biased technology tends to be adopted by plants with high human capital levels, because skill and technology are complementary under strong learning-by-doing conditions. Since plants with more skilled workers are more productive, this hypothesis implies that productive plants are more likely to adopt re-invented technologies.[8] The alternative hypothesis is related to technology leapfrogging. For example, Jovanovic and Nyarko (1996) find an "overtaking" equilibrium in cases where less productive plants switch to a better technology more often than do more productive plants. In their model, productive plants are experienced with regard to old and familiar technologies, while the less productive plants are less attached to technologies. This extensive experience prevents productive plants from adopting a new technology, while less productive plants show a willingness to adopt it. This hypothesis suggests that less productive plants are likelier to adopt re-invented technologies. The direction and severity of the selection bias is an empirical issue. Our specification corrects for this selectivity of furnace technology using the instrumental variable technique.

3.1.2 Estimation Results

Table 3 presents four estimation results, based on methods with the plant fixed effect discussed earlier in this section. Specification (3-A) estimates (1) under the assumption that returns to scale are common across multiple BOF's owned by a plant, while (3-C) allows for different coefficients of capital depending on the number of furnaces. Specification (3-B) accounts for serial correlation in $\varepsilon_{i,t}$, and (3-D) responds to the concern on self-selection regarding the adoption of re-invented technologies. The upper part of the table presents estimates of the regression coefficients. Our inference is based on heteroskedasticity-robust standard errors. The measure of adjusted R^2 indicates that the model fits the data moderately well, accounting for more than 60 percent of the variation in steel output.

We are concerned about endogeneity in input choice. In particular, it is plausible that a more productive plant may be able to make more efficient use of intermediate inputs (labor and electricity) to produce a given amount of steel. This leads to a correlation between the intermediate inputs and the unobserved productivity error. The plant fixed effect specification accounts for the bias.

The coefficients of capacity size and years of BOF use are precisely estimated in (3-A). The elasticity of steel output with respect to the plant-level capacity size is estimated on average as 0.33, indicating the existence of decreasing returns to scale. We further examine the capacity-size variable in (3-C) later in this section. As discussed in the previous section, the variable representing the number of years for which a plant had used the BOF captures the two effects. The estimated coefficient implies that the experience effect dominates the depreciation effect. If a plant uses the BOF for a duration that is greater than the mean

poor performance with small sample size, the property of the data set which our study would likely belong to.

[8] Our data set is unsuitable for testing a hypothesis related to wage premium and human capital. The purpose of the discussion in this paper is to illustrate the importance of controlling for self-selection in the choice of technology.

value by one year, the steel production would increase by 12.7 percent. We examine the presence of serial correlation in $\varepsilon_{i,t}$ by running the following first-order autocorrelation:

$$e_{it} = \rho e_{i,t-1} + \eta_{it}, \tag{3}$$

where $e_{i,t}$ is the residual obtained from estimation (3-A). We find that the p-value of estimated ρ is 0.195, suggesting that the serial correlation may not be a serious concern in our application.

To further delve into the issue of serial correlation, we use the method proposed by Baltagi and Wu (1999). The obtained estimates, presented under (3-B), bears close resemblance to those obtained in (3-A), and the estimated coefficient of $e_{i,t-1}$ is statistically insignificant. We thus conclude that the presence of serial correlation in $\varepsilon_{i,t}$ would make little change to our estimation results.

The specifications discussed so far do not explicitly consider discontinuity in capacity size and assume that returns to scale are common across multiple furnaces owned by a plant that implemented the same technology. All plants possessed multiple BOF's, and the capacity size, in particular, changed only with the number of furnaces operated by a plant. In order to test whether shifting from *n*- to *(n+1)*- furnace operation (where n is an integer greater than zero) changes the capital elasticity of productivity, we estimate different coefficients of capital by the number of furnaces. Due to the small sample size, we employ only the following three cases of plant operation; zero-furnace operations, one- or two-furnace operations, and operations with three or more furnaces. Thus, the model is specified as follows.

$$y_{i,t} = \alpha_{i,t} + \beta_l l_{i,t} + \beta_x x_{i,t} + \beta_{k1} k_{i,t} \times 1\left(0 < N_{i,t} \leq 2\right) + \beta_{k2} k_{i,t} \times 1\left(2 < N_{i,t}\right) + \beta_z z_{i,t} + u_{i,t} \tag{4}$$

where $N_{i,t}$ denotes the number of furnaces for plant i in year t, and $1(\cdot)$ is an indicator equal to one if the expression within parenthesis is true. Hence, β_{k1} (or β_{k2}) measures the differences in the capital elasticities between zero-furnace operations and one- or two-furnace (or three- or more furnace) operations. The other variables and parameters have already been introduced in the previous section. The estimation result is reported in (3-C). The specification uses the fixed-effect method without considering serial correlation. As observed from (3-C), decreasing returns to scale in capital are observed, and the estimated coefficients in the capacity-size variables are neither economically nor statistically different from those reported in (3-A).

Finally, a plant's decision regarding the adoption of the MHL and OG systems would be endogenous if there were a persistent relationship between plant productivity and the adoption timings of the re-invented technologies. This concern would make the variables of re-inventions to correlate with the error in the equation (1). Specification (3-D) attempts to correct for the endogeneity in the variables of the re-inventions included in (1) and (2) by using a two-stage least squared (2SLS) method. Note that the endogenous variables, $MHL_{i,t}$ and $OG_{i,t}$, are continuous, thereby indicating the extent to which the respective technological improvements penetrated at the plant level. We assume that the penetration of each of the re-inventions depends on the following three variables, along with the exogenous variables included in (1), and we treat them as the instruments. First, plant age, representing the number of years for which a particular plant had operated until time t. An older plant may find it more difficult to adopt the re-invented technologies, because the layout of the plant may not be suitable for the installation of technological improvements. This is probably logical in that the old plant, when built, did not anticipate the introduction of the MHL and OG systems. Note that this variable differs from $z_{i,t}$, i.e., years of BOF operation, because many plants existed prior to the introduction of the BOF. The other two instruments represent the average penetration rates of the respective re-inventions for the other plants owned by the same firm. It is possible that experience with re-inventions may have spilled over not only within a plant but also between plants within a firm. These two instruments may be considered as appropriate in the presence of a within-firm experience spillover.

We find in Table 3 that the instruments described above are not weak at the 99 percent confidence level of F-statistics. The estimated coefficients in (3-D) are obtained by regressing the dependent variable onto the exogenous and fitted values of endogenous variables. The results reported in (3-D) indicate that the model does not fit the data well, and the Hausman test would not reject the hypothesis that the plant's decision regarding the adoption of the re-inventions is exogenous. We thus base our inference on the estimates obtaiend from (3-A) to assess the role of re-inventions. The estimates in the coefficients of γ_{MHL} and γ_{OG} indicate that at least OG system improved the productivity of steelmaking: the coefficient of the OG-system variable reported in (3-A) is estimated to be significant both statistically and economically. Since the explanatory variables in (1) are in the logarithmic form, the term $\gamma_{OG} \times OG$ means a percent change in output with respect to the incremental change in the diffusion of the OG system. For example, the estimate imply that Yawata, when it first installed the OG system in 1962, achieved a productivity increase of 12.6 percent. [9] As for MHL, we failed in obtaining the significant result, but the estimated MHL coefficient reported in (3-A) indicates that the re-invention, when fully penetrated across plants (i.e., $MHL = 1$), enhanced the productivity by 1.1 percent. According to the Iron and Steel Institute of Japan (1982: 169), the MHL, when introduced in Yawata, boosted yield by 0.8 to 1.7 percent, and thus the estimated impact of the MHL appears to be consistent with the information obtained from the trade journal.

We analyze the extent to which re-inventions improved the aggregated TFP of the steel industry. We use the estimates obtained from (3-A). Our productivity measure comprises the contributions of re-inventions (represented by the second and third terms in the RHS of (2), and disembodied technical progress (represented by $u_{i,t}$). Industry productivity is calculated annually as the share-weighted average of furnace and plant productivity. Thus, re-inventions are considered to improve industry productivity by the corresponding share-weighted estimates of $\gamma_{MHL} \cdot MHL_{i,t} + \gamma_{OG} \cdot OG_{i,t}$. Figure 2 illustrates that the re-inventions play an essential role in the growth of industry productivity. The estimated contribution of re-inventions toward industry productivity is in general statistically significant, as shown in the 90-percent confidence interval. This shows that the adoption of the MHL and OG systems accounts for about 30 percent of industry productivity. This productivity growth was primarily driven by the OG system, as Table 3 indicates that the estimated impact of MHL is trivial. The estimated industry TFP shown in the figure indicates a high correlation with steel output, wherein the correlation coefficient is 0.66. This finding corroborates with the observation made in Enos (1962), in that "in an industry where startling innovations are relatively infrequent, accumulated improvements (namely, re-inventions in this paper) tend to contribute just as much to technological progress." (Enos, 1962: ix. The authors added the parenthesis).

[9] Yawata installed the OG system for two BOF's out of a total of seven furnaces in 1962; thus $OG_{i,1962}$ takes the value of 0.286. The value of 12.6 is obtained by multiplying 0.286 by the estimate of γ_{OG}.

3.2 Simulation Analysis

In the previous section, our discussion was based on the production-function estimate that re-inventions improved the productivity of steelmaking. In this section, we measure the impact of re-inventions on the growth in industry output by examining the implications on the steel market if Japanese plants had not installed the re-invented technologies and had continued with their BOF refining operation.

The increase in output due to the re-inventions brought profits for the adopters. It would be interesting to examine if the benefits from firms adopting re-invented technologies were equally obtained by firms adopting re-inventions or if they were concentrated to a particular firm, especially a lead-user firm. We conduct the following simulation exercise to examine this issue, while excluding long-run strategies such as the level of production capacity as constant.[10] We assume no adoption of re-invented technologies in the period from 1962 to 1968. This assumption is equivalent to that both $OG_{i,t}$ and $MHL_{i,t}$ take the values of zero, and thus $\alpha_{i,t}$ in (2) equals $\gamma_0 + \gamma_T \log t$. We then solve the firm's optimization problem for each year to obtain the new plant output, holding the disembodied technical progress, $u_{i,t}$, as the estimates. Since the introduction of re-inventions made no changes in the technical features of the BOF steel refining process, we retain the nature of the production function (1) described in the previous section.

We assume that each plant chooses an amount of factor inputs that maximizes its own short-run profit in each year t. [11] The production function (1) contains two factor inputs, namely, labor and electricity. We assume that labor input cannot be chosen by plants in the short-run, because most Japanese companies, including steel producers, vigorously adopted a permanent employment system. Indeed, turnover and layoffs were rarely observed during the study period. We thus consider electricity as the choice variable in the plant's optimization problem. The markets, both for steel output and factor inputs, are assumed to be competitive with regard to the steel price p_t and the electricity price ω_t.[12] Hence, plant i's profit-maximization problem in year t is given by.

$$\max_{X_{i,t}} p_t Y_{i,t} - \omega_t X_{i,t} - FC_{i,t} \qquad (5)$$
$$s.t. \qquad (1)$$

where $Y_{i,t}$ and $X_{i,t}$ denote the exponential transformation of $y_{i,t}$ and $x_{i,t}$ used in (1), and $FC_{i,t}$ denotes the short-run fixed cost, including capital and labor costs for plant i in year t. To assess the counterfactual scenario, we use the estimates from (3-A) in Table 3, replacing the estimated coefficients of $OG_{i,t}$ and $MHL_{i,t}$ in (2) with zeros, and simulate the counterfactual plant output by solving the above optimization problem (5). The obtained simulated output and input for plant i is denoted by $Y^0_{i,t}$ and $X^0_{i,t}$. Following the same procedure, we simulate the model (5) with the actual values of $OG_{i,t}$ and $MHL_{i,t}$, and obtain the predicted values of the steel output for plant i, i.e., $Y^1_{i,t}$. We also denote the corresponding input by

[10] Our simulation exercises do not allow for plant entry and exit. It is probably unreasonable to consider that the absence of re-invented technologies triggers a plant's entry, which is a decision that involves large sunk costs.

[11] Alternatively, we could assume that the firm maximizes its profits by solving its allocation problem across plants. Although this alternative approach may be more realistic, modeling the multi-plant feature requires complex computational issues, which are beyond the scope of this paper.

[12] The steel production process converts pig iron and scrap into crude steel. Thus, our price measure p_{it} is the price of crude steel, netted out of the sum of the pig iron and scrap prices.

$X^1_{i,t}$. The industry outputs are calculated by summing over the obtained outputs across all plants as follows: $Y^0_t \equiv \sum_i Y^0_{i,t}$ and $Y^1_t \equiv \sum_i Y^1_{i,t}$. The difference in the two output indices, Y^0_t and Y^1_t, shows a significant contribution of re-inventions to the growth of Japanese steel output. The difference between the two series diverged as re-invented technologies penetrated across plants. The comparison of the estimates shows that re-inventions increased the level of steel output by 14.3 percent, and the rate of output growth by 3 percent. When the improvements were fully distributed in 1968, the re-inventions enhanced the steel output by 19.8 percent. Therefore, the re-inventions accounted for approximately a quarter of the steel output in the 1960s.

We maintain the assumption of perfect competition for both the product and factor markets of steel, and assume that the values of the fixed costs, $FC_{i,t}$, are unaltered, regardless of whether or not plants installed the MHL and the OG systems. The profit accrued to plant i that adopted the re-invented technologies is simulated as follows.

$$\begin{aligned}\Pi^1_{i,t} - \Pi^0_{i,t} &\equiv \left(p_t Y^1_{i,t} - \omega_t X^1_{i,t} - FC_{i,t}\right) - \left(p_t Y^0_{i,t} - \omega_t X^0_{i,t} - FC_{i,t}\right) \\ &= p_t \left(Y^1_{i,t} - Y^0_{i,t}\right) - \omega_t \left(X^1_{i,t} - X^0_{i,t}\right),\end{aligned}$$

where $\Pi^1_{i,t}$ (or $\Pi^0_{i,t}$) represents plant i's simulated profit in year t under the assumption that both $OG_{i,t}$ and $MHL_{i,t}$ take the actual values (or take the values of zeros). Thus, the difference between $\Pi^1_{i,t}$ and $\Pi^0_{i,t}$ indicates the additional monetary benefits obtained from a plant's adoption of re-invented technologies. The simulation results presented in Table 4 [13] show that the inventing company, Yawata, was the largest beneficiary of re-inventions; in our data set, Yawata's benefit from the re-inventions was about 30 percent larger than that of the second largest beneficiary, Fuji. The result is robust in the absence of MHL. This finding appears to indicate that Yawata, with the largest BOF production in the Japanese steel market, was most motivated to create the MHL and OG systems. The results from our ex-post simulation exercise analyzed in this section are consistent with the hypothesis proposed in von Hippel (1986) that Yawata fits the lead-user role in the creation of the MHL and particularly OG system.

4 Conclusion

New technologies often appear in a rough form. A long process of improvements is usually required in order for such technologies to successfully prevail in the economy. This process of improvements occurs on the sides of both producers as well as users. In this paper, we focused on the role of users in technological improvements. It is anticipated, especially in the area of computer software, that users are playing an increasingly important role in such innovative activities. Moreover, there has been scarce empirical research to identify and assess the importance of re-inventions.

Using the unique example of the Japanese steel market, this paper empirically examined the economic significance of re-invented technologies. The paper investigated two such re-inventions that were created in Japan, namely, the MHL and OG systems. Both resolved technical problems inherent in the use of BOF steel refining technology and improved its performance. The distinctive feature of these technological improvements is that the MHL and OG systems were created by a user and not by a manufacturer of the

[13] Note that we do not provide confidence interval for $\Pi^1_{i,t} - \Pi^0_{i,t}$, which is complicated non-linear combination of estimates.

BOF. This paper examined the extent to which re-inventions affected industry output and productivity. The estimates of the production function indicated that the re-invented technologies accounted for approximately 30 percent of the steel making productivity. The simulation results showed that the steel output in Japan would have lowered by 14 percent without re-inventions. The paper also illustrated that the benefits of re-invented technologies were concentrated to the innovating company, Yawata. This paper subscribed to the view stated in trade journals and argued that re-inventions in the Japanese steel refining process in the 1960s are consistent with the "lead-user" hypothesis proposed in von Hippel (1986). This paper corroborated that Yawata benefitted most from re-inventions and states that Yawata freely disclosed pertinent information concerning the technical details and the performance of their technological improvements to their domestic competitors.

Although it focused on one specific example of steel refining technology, this paper quantitatively identified the fact that re-invented technologies contributed significantly to industry growth and presumably to the economy. It is, however, important to note that the paper's analysis is ex-post; that is, we considered successful re-inventions with the benefit of retrospection. Although it is extremely difficult to collect data, one avenue for future empirical research on re-inventions is to choose examples, preferably drawn from a random sample based on ex-ante perspective. This will enable the study of not only successful re-invented technologies but also failed or ineffectual innovations.

A Data Appendix

Our data set comprises annual plant-level data describing 19 plants and 8 Japanese steel firms for the period 1957 — 1968. The output and input data (except for labor and physical capital, as described below) were obtained from the Japan Steel Federation (1955 – 1970). The data cover approximately 95 percent of the total steel production throughout the study period. We focused on crude steel as the output. With regard to the input, we collected data on the amount of electricity. Over 90 percent of the plants covered in the data operated more than one furnace in a given year.

Data concerning labor input were constructed from the following two data sets: the number of workers at the plant level (obtained from the Japan Steel Federation, 1955 – 1970) and the actual work hours averaged over workers at the firm level (obtained from the The Tekko Shimbun Co, 1955 – 1970). Data concerning the number of workers were not disaggregated by furnace, unlike the other input data obtained from the same source. This construction of the labor data is due to the fact that plant workers often operated both types of furnaces. The labor input used for the estimation is expressed in terms of total man hours, which is constructed from the number of plant-level workers multiplied by the actual work hours averaged over workers at the firm level. Data pertaining to furnace capacity by plant was obtained from companies' semiannual financial reports, which identify all furnace capacities for the 19 plants covered in our data. The data recorded the capacity at the end of year t, and an investment was made only when a new furnace was built.

References

[1] Ackerberg, D.A., K. Caves, and G. Frazer. (2005), "Structural Identification of Production Functions," working paper.

[2] Allen, R.C., 1983, "Collective Invention," *Journal of Economic Behavior and Organization*, 4: 1-24.

[3] Arellano, M., and S. Bond. (1991). "Some Tests of Specification for Panel Data: Monte Carlo Evidence and An Application to Employment Equations," *Review of Economic Studies,* 58: 277-297.

[4] Baltagi, B. H., and P. X. Wu. (1999), "Unequally Spaced Panel Data Regressions with AR(1) Disturbances," *Econometric Theory*, 15: 814-823.

[5] Caselli, F., 1999, "Technological Revolutions," *American Economic Review*, 89(1): 78-102.

[6] Enos, J. L., 1962, *Petroleum Progress and Profits: A History of Process Innovation*, The MIT Press, Cambridge.

[7] Hogan, W.T., 1971, *Economic History of the Iron and Steel Industry in the United States*, Lexington.

[8] Hollander, S., 1965, *The Sources of Increased Efficiency: A Study of Du Pont Rayon Plants*, The MIT Press, Cambridge.

[9] Iron and Steel Institute of Japan, 1982, *History of Basic Oxygen Furnace in Japan*, Tokyo.

[10] Japan Steel Federation. (1955-1970), *Reference Material on Steel Making*, Tokyo.

[11] Jefferson (1990), "China's Iron and Steel Industry: Sources of Enterprise Efficiency and the Impact of Reform," *Journal of Development Economics*, 33: 329-355.

[12] Jovanovic, B. and Y. Nyarko. (1996), "Learning by Doing and the Choice of Technology," *Econometrica*, 64: 1299-1310.

[13] Klette, T.J. and Z. Griliches. (1996), "The inconsistency of common scale estimators when output prices are unobserved and endogenous," *Journal of Applied Econometrics*, 11: 343-61.

[14] Lerner, J., and J. Tirole., 2002, "Some Simple Economics of Open Source," *Journal of Industrial Economics*, L(2): 197-234.

[15] Levinsohn, J. and A. Petrin. (2003), "Estimating Production Functions Using Inputs to Control for Unobservables," *Review of Economics Studies*, 70: 317-341.

[16] Lynn, L.H., 1982, *How Japan Innovates: A Comparison with the U.S. in the Case of Oxygen Steelmaking*, Boulder, Colorado, Westview Press.

[17] Nakamura, T., and H. Ohashi. (2008), "Effects of Technology Adoption on Productivity and Industry Growth: A Study of Steel Refining Furnaces," *Journal of Industrial Economics*, 56(3), 470-499.

[18] Nelson, R.R., and S.G. Winter (1984), *An Evolutionary Theory of Economic Change*, Harvard University Press, Cambridge.

[19] Nuvolari, A., 2004, "Collective Invention during the British Industrial Revolution: the Case of the Cornish Pumping Engine," *Cambridge Journal of Economics*, 28: 347-363.

[20] Odagiri, H. and A. Goto. (1996), *Technology and Industrial Development in Japan: Building Capabilities by Learning, Innovation and Public Policy*, Chapter 7, Oxford University Press.

[21] Ohashi, H. (2005), "Learning by Doing, Export Subsidies, and Industry Growth: Japanese Steel in the 1950s and 1960s," *Journal of International Economics*, 66: 297-323.

[22] Olley, S. and A. Pakes. (1996), "The Dynamics of Productivity in the Telecommunications Equipment Industry," *Econometrica*, 64(6), 1263-1298.

[23] Rogers, E.M., 2003, *Diffusion of Innovations*, 5th-Edition, New York, Free Press.

[24] Satomura, H. (1971), *Seisan-sei no Sokutei* (Measurement of Productivity), Toyo Keizai Shinposha, Tokyo.

[25] Sutton, J. (2005), "Market Share Dynamics and the 'Persistence of Leadership' Debate," presented at the European Economic Association, 2005.

[26] The Tekko Shimbun, Co. (1955-1970), *Tekko Nenkan*, Tokyo.

[27] Tyler, W. G. (1979), "Technical Efficiency in Production in a Developing Country: An Empirical Examination of the Brazilian Plastics and Steel Industries," *Oxford Economic Paper*, 31(3), 477-495 .

[28] von Hippel, E. (1986), "Lead Users: A Source of Novel Product Concept," *Management Science* 32(7): 791-805.

[29] von Hippel, E. (2005), *Democratizing Innovation*, MIT Press, Cambridge.