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ABSTRACT

Tweaking and the Horndal effect*

We document the evolution of productivity in a steel mini mill with fixed capital, producing an unchanged product with Leontief technology. Despite the fact that production conditions did not change dramatically, production doubles within the sample period (almost 12 years). We decompose the gains into: downtime reductions, more rounds of production per time, and more output per run. After attributing productivity gains to investment and an incentive plan, we are left with a large unexplained component. Learning by experimentation, or tweaking, seems to be behind the continual and gradual process of productivity growth. The findings suggest that capacity is not as well defined, even in batch-oriented manufacturing.

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1 Introduction

Productivity growth and dispersion are of great importance for the understanding trade, business survival, and economic growth. While recent empirical work (surveyed in Syverson, 2012) has documented substantial heterogeneity across plants, and changes over time (Collard-Wexler et al., 2012), there is little agreement about the source of these differences and changes. The main hurdle to quantifying the evolution of productivity, and its determinants, is the availability of data, good enough to match the complexity of the measurement challenges. Griliches (1996) provides a history of the challenges faced by the literature since its beginnings. The challenges range from conceptualizing good managerial practices to properly measuring inputs and outputs. Firms typically produce a range of products, of varying prices, and it is not obvious how to aggregate them into a single output measure. In addition, often revenues rather than output are observed. Many inputs, such as labor, are heterogeneous and hence hard to aggregate. Capital is particularly hard to quantify; typically only accounting data is available, but such data reflect outlays and depreciation rules, which are not necessarily economically meaningful (Fisher et al., 1983).

In this paper we try to shed some light on the sources and evolution of productivity growth by looking at a single firm, for which we have access to very detailed output and input data. The firm we study is a steel melt shop which produces steel billets using a very traditional, arguably Leontief technology. Despite the absence of dramatic changes in economic conditions, the melt shop almost doubled its annual production in tons of billets over a 12 year period. While studying a single plant limits the take away, and generalizability of the findings, both data and the product itself may prove quite useful. The simplicity of the product avoids many of the measurement problems, while the detailed data enables us to look at the sources of productivity gain.

The data avoids many of the measurement challenges just described. First, the melt shop produces a single homogenous product, steel billets, which is a well-defined, internationally traded, commodity. Hence, we are able to cleanly measure output in physical units (as opposed to revenue or bundles of products). Second, capital, which is typically hard to measure, is also well defined in this case. The melt shop used the same furnace to melt the scrap throughout the sample period, meaning that capital, and thus capacity, remained fixed.[1] Third, while labor quality and heterogeneity is typically a concern, the melt shop suffered almost no labor turnover, and kept working in three daily eight-hour shift, on a 24/7 basis, virtually throughout the entire sample period. Fourth, we were granted access to very detailed production and cost data (even daily input utilization and output for a good part of sample period) that enable us to decompose the source of the productivity gain in an unusually detailed way.

The steel melt shop we study uses a traditional "mini mill" technology, where steel scrap is

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[1] There was investment in the meltshop over the sample period. We will use the timing of investment to find its effect on productivity.

melted in an electric arc furnace (EAF) in batches, or heat cycles (Heats, henceforth). The molten steel is then processed in a ladle furnace (LF), and cast into billets, using a continuous casting machine (CCM). The billets are then rolled in a rolling mill to produce concrete reinforcing bars (rebars), which are an important input in the construction industry. Steel billets are an internationally traded commodity; for example, steel billets are traded at the London Metal Exchange, along with futures and options contracts.

Figure 1 shows the monthly average of the daily production of billets in tons over the sample period.[2]

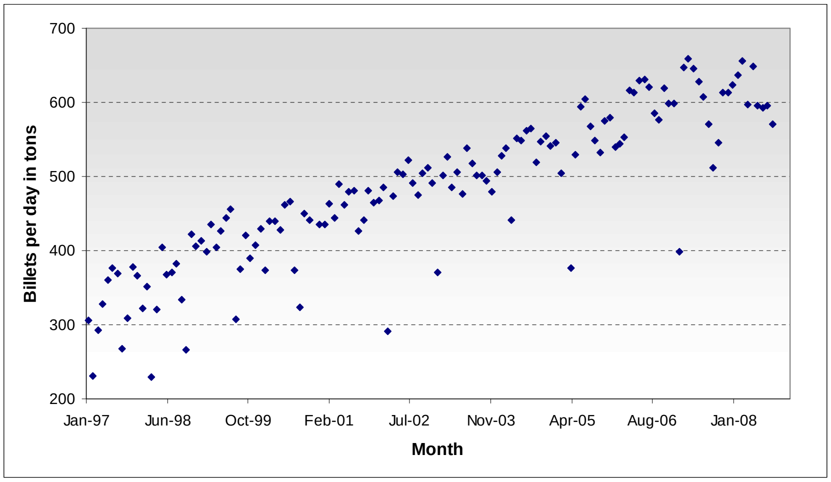

Figure 1: Monthly average of daily production of billets in tons
January 1997 - September 2008

Figure 1 displays several remarkable facts. First, the daily production of billets doubled in a span of almost 12 years, from around 300 tons per day at the beginning of 1997, to around 600 tons per day by mid 2008. This is especially striking given that there were no major changes in production conditions. Second, while the steelmaker improved the furnace (though did not change its size) and introduced an incentive scheme for its employees, we do not spot jumps in output commensurate with discrete production enhancements. Third, output growth is gradual and continuous, suggesting that a flow of small improvements to the production process took place.[3] It appears as if small improvements, or "tweaks," might be necessary to exploit the potential gains created by new equipment or practices, otherwise jumps would be observed.[4]

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[2] We show the monthly average of the daily production level (rather than the monthly production levels) to eliminate fluctuations in total production levels from one month to another due to month length.

[3] Indeed, the steelmaker's management, as well as other experts we talked to, stressed that a sequence of small improvements (i.e., tweaks) in the production process is needed for improvement in billets production and for getting the best out of new equipment and practices.

[4] The notion that "tweaking" existing technologies can be an important source of economic growth and techno-

We describe the technology, and propose a production function, at the batch or heat level, which suggests a natural output decomposition. The decomposition of the productivity gains shows that the melt shop was able to increase its daily output of billets, despite not changing the size of the furnace, through the following means: (i) an increase in plant utilization by cutting the number and length of shut downs, disruptions, and delays,[5] (ii) an increase in the number of heats per each 24 hours of continuous operation ("effective day"), and (iii) an increase in the billets output per each heat. We document the evolution of these three output components; which we then relate to the timing of investments and the introduction and adjustment of the incentive scheme, to evaluate which of the changes might be responsible for the observed gains.

We find that during the $1997-2001$ period, the gains in production are mainly due to better plant utilization, from below 80% to above 95% of the time. This increase was achieved through minimizing downtimes (basically, cutting repair delays and maintenance time). Starting in 2001, there is a steady and gradual increase in the number of heats per –effective– day. The length of heat depends on the speed with which scrap is fed into the EAF, the speed with which it is melted in the EAF, and the speed with which it is poured to and processed in the LF, and cast in the CCM. The quantity of billets per heat remained stable until 2004, but then trended up until 2008.

There are several candidate explanations for the increase in productivity. First, interviews with management suggest the firm overcome an adversarial relation with labor during the first years of operation. Second, improvements in the EAF, LF, and CCM, took place during the sample period. Third, the firm adopted an incentive scheme in June 2001 and adjusted its parameters twice following improvements in the EAF and LF, to increase effectiveness (more details below). We relate the timing of the improvement in plant hours, heats per day, and billets per heat, to the timing of the different changes (physical and worker incentives). The goal is to attribute the gains to specific changes, and as a by-product to figure out what proportion of the overall gain in productivity remains unexplained by these actions.

We find that a 14.4% increase in production can be attributed to the incentive scheme. The channel through which incentives affected production is heats per day. Incentives do not seem to have had a significant effect in plant utilization or on billets per heat. Another 19.7% increase in production can be imputed to several capital improvements. The unexplained part of productivity growth, which cannot be attributed to observed changes, is quite substantial and amounts to a 2.9% annual productivity growth.

We do not know what enabled the productivity growth. We just observe a gradual process,

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logical progress is advanced in Meisenzahl and Mokyr (2012) who stress the importance of "tweakers" to explain the technological leadership of Britain during the Industrial Revolution.

[5] As mentioned earlier, the melt shop was active on a 24/7 basis throughout the sample period. When the furnace is not active due to planned or unplanned shut downs, the workers engage in repairs and maintenance work, so the melt shop is still active even if it is not melting scrap and casting of billets.

and continuous increase in production over a period of close to 12 years, despite the technology being traditional, known and used for many years in the same plant, with virtually the same workers. Conversations with management suggest that they believe that the productivity gain can be attributed to "learning through experimentation" or "tweaking the production process." For instance, small changes over time in the way scrap is fed to the furnace and in the timing of the different tasks performed. It is a form of learning, but it is somewhat different from learning from past production as modeled by Arrow (1962), since here the driving force does not seems to be past output per-se, but rather experimentation and tweaking, based on trying new ways to execute each step of the production process. The improved relations with labor were an essential component of the innovation process. The cooperative environment is necessary for the continuous stream of improvements, since the latter are mostly initiated and proposed by the workers themselves.

The findings suggest that capacity is not a well defined, fixed ceiling on output. Typically, capacity is considered as a biding constraint on output, which can be relaxed only through physical investment. Our findings indicate however that tweaking the production process can expand capacity substantially, even when physical capital is fixed. It is more stretchable, an elastic yardstick. Moreover, it appears that microinnovations (Mokyr, 1992) are necessary to fully exploit physical changes. In particular, our data shows that tweaking can last for a long time and can go a long way. Standard production function estimation may miss the actual impact of capital improvements, or other innovations, if these types of tweaks are necessary to exploit physical improvements. Output may be slow to respond to investment, making difficult to estimate its impact on production.

The proposed explanations leave many unanswered questions. What makes the progress so slow, given the traditional technology? Why wasn't the previous management able to achieve these gains? Perhaps the answer is that the continuous tweaking, of trial and error, requires good labor-management relations.

The rest of the paper is organized as follows. In Section 2 we discuss the relevant literature in order to place our study in context. Section 3 provides some background on the steel mill that we study. Section 4 describes our data set. Section 5 presents our main findings. We conclude in Section 6.

2 Related Literature

The process of gradual increase in output despite the lack of investments is referred to in the literature as the "Horndal effect." The effect was introduced by Lundberg (I961) who showed that productivity at the Horndal steel works in Sweden increased by 2% per year on average between 1935 − 1950, despite the lack of significant capital investments. Arrow (1962) argues that this steady increase in productivity at the Horndal "can only be imputed to learning from experience." David (1973, 1975), like Arrow, attributes to "learning by doing" a similar productivity growth observed in a textile mill in Lowell, Massachusetts from 1835 to 1856, despite the absence of investment in new machinery.

Later papers revisited the productivity growth at Horndal and Lowell. In a detailed study of the Horndal steel works, Genberg (1992) attributes the productivity growth to a complex set of factors, including minor alterations to the capital equipment, the introduction of organizational change, such as central planning and the division of tasks between the plants in the company group, and an increase in the work effort on the part of labor. Genberg concludes that "pure productivity growth" is only a small part of the story.

Lazonick and Brush (1985) use detailed production and payroll records to conclude that a "production-relations" effect, which arises due to social factors, and in particular management-worker relations, which boost workers' effort, was behind Lowell's case. Bessen (2003) argues that the Horndal effect at Lowell was due to the fact that the mill changed the composition of its workers, from mostly temporary Yankee farm girls to local residents who stayed longer on the job, and hence were more experienced and able to benefit from on-the-job learning. This allowed the mill to switch permanently from two looms per worker to three looms per worker in 1842, and then to four looms per worker after 1851.

Thompson (2001) makes the point that a large part of the productivity gains attributed to learning, in shipbuilding during World War II, were due to massive capital improvements, that went unmeasured. He also shows that the quality of ships, as measured by the fracture rate, declined systematically with labor productivity and production speed. Sinclair, Klepper, and Cohen (2000) study detailed data on a large manufacturer and specialty chemicals products over a two and one half year period. They argue that the reason why cumulative past output is positively correlated with cost reduction is not due to passive learning per se, but rather to the fact that cumulative output is associated with higher expected future output, which in turn boosts the firm's incentive to engage in R&D, which in turn lowers the cost of production.

Tether and Metcalfe (2003) study a Horndal effect in some of Europe's most congested airports in 1990's, including Heathrow, Gatwick, Frankfurt, and Charles De Gaul. The capacity of these airports to handle flights has increased over the 1990's despite retaining the same basic infrastructures.[6] Tether and Metcalfe distinguish between four types of learning by doing: individual learning (which they argue is mostly passive), learning within a team, learning between teams (which they argue is particularly associated with minor modifications to technologies), and learning by cooperating (teams do not only interact with each other but are also interdependent). They attribute a large part of the Horndal effect in the airports capacity to learning by cooperating.

Similarly to our paper, there are two recent papers that document significant productivity increases in a single plant despite any substantial changes in capital or labor. Das et al. (2012)

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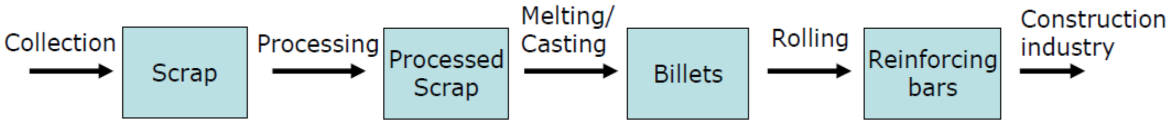
[6] For example, Heathrow's runway capacity grew by 14% during the 1990's, without changes to runway system and despite the experts' belief that there was no further scope for expansion.

examine data on the floor-level operations at the largest rail mill in India in the early 2000s. During that period, the mill's position as the sole supplier of Indian Railways was threatened due to concerns about the quality of its rails and its ability to meet the increased demand for rails. In response, the mill initiated a variety of programs intended to motivate and train workers and control absenteeism. Between $2000-2003$, total shifts worked went up by 15%, the average output per shift increased by 28%, the number of defects was cut in half, and delays caused by employee errors went down by 43%. Das et al. are able to attribute over half of the increase in output to productivity training aimed at lowering the probability of delays caused by employee mistakes and malfunctioning machinery.

Levitt, List, and Syverson (2012) study detailed data from an assembly plant of a major auto producer and find considerable evidence of learning by doing: defects per vehicle fall more than 80% in the first eight weeks of production. The plant's productivity gains seem to be embodied in the plant's physical or organizational capital rather than in specific workers as the defect rates observed on the second shift are below those observed contemporaneously on the first shift, even though the first shift had a nearly two months head start in production. They also find that defects in one car spill over to other cars following nearby on the assembly line. In contract to this paper that reports a substantial learning in matters of weeks, we document a gradual and continuous process over years.

3 Background and Production Function

The melt shop we study is owned by a vertically integrated steelmaker, that uses the entire production of billets in house to produce concrete reinforcing bars (rebars). If the quantity of billets produced is insufficient, the steelmaker buys additional billets in the market. The production process of rebars is illustrated in the following figure:



Scrap is collected, mainly by independent scrap collectors, and then processed in the steelmaker's scrap yard in order to clean it up from other materials that can harm the quality of the billets (e.g., copper, tin, and zinc), and cut and press into relatively small pieces that can be fed into to the furnace. The processed scrap is then melted in the melt shop and cast into steel billets, which are then sent to rolling mills, to be rolled into concrete reinforcing bars (rebars). Rebars are either sold to construction companies or used as an input in cut-and-bend plants that manufacture prefabricated rebars according to constructors' specifications.

Our study and data focus on the production of billets in the melt shop.[7] As mentioned earlier, the production process in the melt shop is traditional: it begins with layering processed scrap into a basket according to size and density. The scrap is then charged into an EAF through a retractable roof. An electric current is then passed through electrodes to form an arc, which generates heat that starts the melting process. To accelerate the melting process, oxygen is blown into the scrap, and other Ferro alloys are added to give the molten steel its required chemical composition. During the heat cycle, which lasts for about an hour, the retractable roof of the furnace is opened twice more and two additional rounds of scrap baskets are charged into the EAF. At the end of the heat cycle, the molten steel is poured into a preheated LF, where it undergoes LF metallurgy refining treatments for precision control of chemistry. The molten steel is then moulded into billets in the CCM.

The mini mill technology that the steelmaker is using has been in commercial use since the early 1900's, although it became widely used only in the 1980's following the success of Nucor, which is by now the largest steelmaker in the U.S.[8] The production technology can be perceived as Leontief technology, as steel scrap, energy, labor, and additional materials (Oxygen, Ferro alloys, lime, etch) are combined in fixed proportions to produce rebars. In particular, one cannot produce more rebars with less scrap. The main determinant of a mini mill's capacity is the size of the furnace. The average capacity of U.S. mini mills in 2003 was $940,000$ tons per year and the median was $750,000$ tons per year (Giarratani, Madhavan, and Gruver, 2012, Table 3). The mini mill we study is relatively small, as its annual production grew from $117,000$ tons of billets in 1997 to $215,000$ tons in $2006 - 2007$.

3.1 The Production Function

Production functions reflect the output produced by a given amount of inputs, like labor, capital, and energy. The textbook description of production functions does not explicitly state the time period during which output is being produced. But implicitly the production function refers to a time period during which the inputs are dedicated to production. We will make explicit reference to time.

As mentioned earlier, production at the melt shop is organized in batches, called heats. We find it useful to consider the productivity gains associated with more output per batch, and the time it takes to run a batch. While both components contribute to productivity, decomposing them, will enable us to associate different gains with different changes at the plant.

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[7] For an excellent overview of the production process in an EAF meltshop, see Jones J. "Electric Arc Furnace Steelmaking," American Iron and Steel Institute," http://legacy.steel.org/AM/Template.cfm?Section=Home&TEMPLATE=/CM/HTMLDisplay.cfm&CONTENTID=12308

[8] For an overview of the steel industry, see Scherer (1996). Collard-Wexler and De Loecker (2012) study the productivity gains due to transition into mini mills in the US.

Since production is organized in batches, it is natural to model the production function at the heat level. We will model both aspects of productivity: output per heat as well as the speed of the heat. The two components are then combined to describe the production function per unit of time. Arguably, production at the heat level involves a Leontief technology, as scrap and various Ferro alloys are mixed in fixed proportions to create steel billets. But the time it takes to complete a heat depends on energy used (both electric and chemical), labor or labor motivation, and know-how.

The output of each heat, measured in tons of billets per heat, y_h, is limited by the scrap input being used, as well as by the production capacity which depends on the EAF's capacity to melt scrap, the LF's capacity to process the melted scrap, and the CCM's capacity to cast the billets. The production technology can therefore be represented as:

$$y_h = \min\left\{a_{EAF} \cdot k_{EAF}, a_{LF} \cdot k_{LF}, a_{CCM} \cdot k_{CCM}, a_s \cdot s\right\}, \tag{1}$$

where s represents the scrap input, k_{EAF}, k_{LF}, k_{CCM}, represent capital –or capacity– associated with the EAF, LF, and CCM. a_s, a_{EAF}, a_{LF}, a_{CCM} are the Leontief coefficients. Technological progress can be perceived as improvements in these coefficients.

Naturally, workers and energy are needed for production. These inputs determine the time it takes to complete a heat. The length of a heat depends on the number of workers, the speed with which they work (i.e., workers "run rather than walk"), and how diligent they are (more diligence is likely to cut on the number and severity of human errors). Likewise, the amount of energy used is likely to influence the length of the heat (more energy can speed the melting process, in some range).

The time required to complete a heat, T_h, can be postulated to be:

$$T_h = \frac{g(e, l, s)}{A}, \tag{2}$$

where A represents productivity (or know-how), in terms of speed of production unaccounted by inputs; e is energy and l is production workers. The function g is expected to decline in the first two arguments and increase with the third, in some range. Labor, l, captures not only the number of workers, but may also effort.

The number of heats the firm can perform during a day is:

$$h(A, e, l, s) = \frac{24}{T_h}.$$

Another constraint on output is the ability to productively utilize capital. Shut-down, due to disruptions, repairs and maintenance limit output. Let's denote plant utilization at time t by U_t. Utilization may depend on managerial practices. The time index t reflects the idea that plant utilization may change over time for reasons unrelated to the factors we measure.

The three components: plant utilization, U_t, heats per day, $h(A, e, l, s)$, and billets per heat, y_h, can be combined to define the production function, as usually represented, as output per inputs, during a period of time:

$$y_t = F(U_t, A, e, l, k, s) = U_t \ h(A, e, l, s) \ \min\{a_k k, a_s s\} \tag{3}$$

where a_k represents the vector $(a_{EAF}, a_{LF}, a_{CCM})$ and k represents the vector $(k_{EAF}, k_{LF}, k_{CCM})$.

The Leontief part of (3) represents the bottlenecks in the production of billets in each heat, namely, capacity and scrap. The Leontief part is augmented by a function of e and l, which captures the number of heat per day, dictated by the time it takes to complete each heat. Finally, output increases linearly in utilization, U_t, as more heats can be accommodated the more the capital is utilized. Technological progress in output at the batch level is captured by changes in a_k, while progress in the time it takes to complete a heat are captured by A, both a_k and A are indexed by t (omitted here for simplicity).

The production function suggests that improvements in output come either through (i) better utilization of the melt shop which we will measure as $\frac{\text{Effective days}}{\text{Days}}$, (ii) an increase in the number of heats per day, represented by $\frac{\text{Heats}}{\text{Effective days}}$ and (iii) an increase in the output of billets per heat. We thus consider the following output decomposition:

$$\frac{\text{Billets}}{\text{Days}} = \frac{\text{Billets}}{\text{Heat}} \times \frac{\text{Heats}}{\text{Effective days}} \times \frac{\text{Effective days}}{\text{Days}} \tag{4}$$

The ratio on the left-hand side, is our measure of output. We compute it by diving the monthly output of billets in tons by the number of days during the month. As mentioned earlier, we use this measure in order to account for the fact that some months have 31 days and hence have more output than months with $28-30$ days.

The plant utilization measure, $\frac{\text{Effective day}}{\text{Days}}$, is based on "Effective days," which is the total number of hours of plant operation in a given month, divided by the number of hours in the same month. This gives us the number of full days the melt shop was up and running during the month (i.e., "effective days").[9] Dividing "effective days" by the number of days in the month gives us the percentage of time during the month in which the melt shop was up and running. The second ratio, $\frac{\text{Heats}}{\text{Effective days}}$, is our measure of heats per effective day of operation. It is computed by dividing the total number of heats in a given month by the number of effective days during that month. Finally, the ratio, $\frac{\text{Billets}}{\text{Heat}}$ is computed by dividing the output of billets in tons in a given month by the total number of heats during that month.[10]

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[9] Recall that the plant operates 24/7 (with the exceptions discussed in the next section, mainly associated with improvements). Effective days reflect the plant hours in wihch the furnace is working. In an hour of non-operation, a non-effective hour (no heats are performed), workers are in the plant doing maintenance and repairs.

[10] In computing the averages, we eliminated from the computation of billets per day and plant utilization some months in which the melt shop was shut down for planned renovation. These months include March 1998, March 2002, January 2003, March-April 2005, February 2007, and October-November 2008.

While we would like to estimate the production function in (3), both labor and capital are fixed, aside from some improvements, during our sample. So there isn't much scope for estimating a production function. Instead, we will regress each of the components on the events at the plant, using the production function in (3) as framework to interpret the different improvements. For example, one would expect the incentive scheme to enhance labor in (2), while physical improvements are likely to enter through (1). Moreover, one can test for a physical improvement looking for jumps in scrap utilization (more below).

4 Data

The melt shop was acquired by the current owner several years prior to 1997, the start of the data. Interviews with the firm's CEO indicate that production did not change much from the time the firm was acquire until 1997. During this period, the new management team was mainly occupied with figuring out how to operate the melt shop efficiently and with improving relationship with the melt shop's work force (these relationship were strained under the previous management team).

We have daily data from May 2001 to August 2009 (though daily data is missing for June 2001) on production, output, every input utilized, and the time spent on production and on delays. In what follows, we will study data only until September 2008, after the global financial crisis erupted. The reason to stop at the pick of the financial crises is that it had an impact on the profitability of production and following September 2008, the melt shop chose in some months to operate at less than full capacity, which it never did during the January 1997 to September 2008 period. For January 1997 to April 2001, we only have monthly data on production.

The next table shows summary statistics of the production data.

Table 1 – Summary statistics: production (all variable are per month)

	Obs.	Mean	S.D.	Min	Max	Dates of Obs.
Production days	140	27.2	3.5	4.71	30.33	Jan 1997-Sep 2008
Plant Hours	140	652.3	84.6	113	728	Jan 1997-Sep 2008
Heats	140	589.3	112.8	107	764	Jan 1997-Sep 2008
Tons of Billets	140	$14,520.8$	$3,323.5$	2656	$20,345$	Jan 1997-Sep 2008
Scrap used in tons	140	$16,530.1$	$4,095.2$	3067	$24,291$	Jan 1997-Sep 2008

Dec 2000 is missing

As Table 1 shows, on average, the melt shop was operating for 26.8 days, or 642.8 hours, a month, performed 586.1 heats per month, which amounts to 21.87 heats per each full day of operation, and produced $14,502.5$ tons of billets a month, using $16,515.7$ tons of scrap. The average ratio between tons of good billets produced and tons of scrap used as an input (the "yield rate") was then 88%. Most of remaining 12% of scrap used is slag (oxidized impurities), which is sent to a landfill, and the rest is dust, which is sold to a cement producer as raw material.

4.1 Prices and Cost Data

Steel scrap, billets, and rebars are all relatively homogenous products, which are traded on world markets and their prices are quoted on a daily basis in various trade publications. There are many different grades of scrap; traded at different prices. The two most common grades are HMS 1 and HMS 2 (Heavy Metal Scrap). The following figure shows that monthly average price per ton of HMS 1 and HMS 2, as well as the international monthly prices of billets and rebars. The prices are taken from *Metal Bulletin*, which is a leading trade publication in the steel industry, and is used by the steelmaker's own management as a reference.

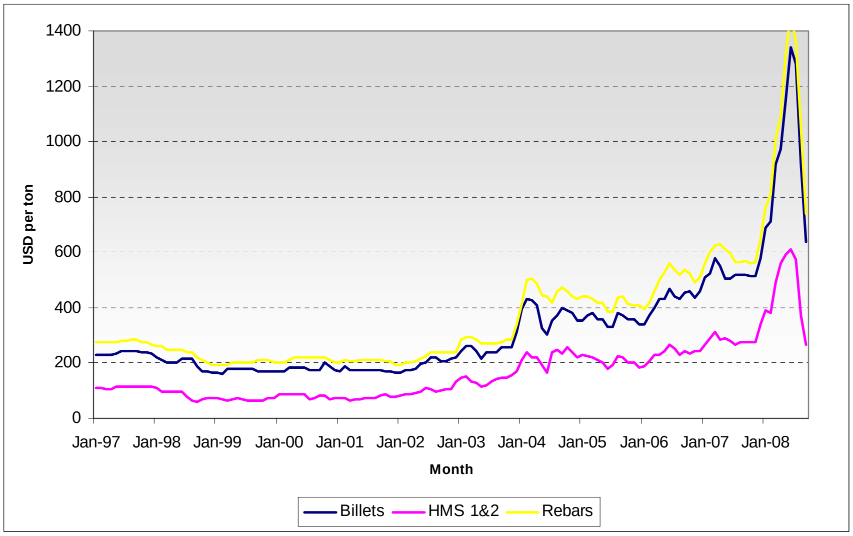

Figure 2: The international prices of scrap, billets, and rebars

The local market is open to imports and exports. Scrap is exported, so its local price is strongly correlated with the intentional price of scrap. Billets and rebars are imported by other rolling mills. The effective price of billets from its thus the international price plus transportation costs.

In addition to prices, we also have data on the actual prices the melt shop paid for inputs and hence on the melt shop's actual cost. The following table presents the share of the main cost items out of the total cost of billets (excluding capital):

Table 2 – The share of the main cost items out of total cost January 1997-September 2008

Cost item[11]	Share in total cost in %
Scrap	54.9
Electricity	11.0
Labor	6.0
Ferro Alloys	4.5
Maintenance materials and subcontracted labor	4.5
Refractories	3.8
Depreciation	3.6
Electrodes and Nipples	3.0
Propane gas	2.6
Oxygen	2.5
Lime	1.3
Other material, Municipal taxes, and insurance	2.3
Total	100

*Missing data for Dec 2000 and Nov-Dec 2003.

As Table 2 shows, the main cost driver of billets is scrap, which accounts for more than a half of the total cost of billets. The next large cost driver is electricity, which accounts for about 10% of total cost. Labor (both regular workers and subcontracted labor) account for about 8% of total cost, and Ferro alloys, and maintenance account for slightly over 4% each.

4.2 Investments and incentive scheme

Over the sample period (almost 12 years), the steelmaker invested about 25 Million USD in the melt shop. This amounts to about 3% of the total value of billets produced over that same period. While we do not have a complete breakdown of investment, we do know the timing of a couple of specific improvements. It is possible that other improvements were undertaken which we do not know about.

Major upgrades require shutting the plant down. Since we have daily data for most of the sample period, we know when the melt shop was shut down. We will date all periods during which the melt shop was not operating, and will use the timing of these downtimes to estimate whether a

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[11] Refractories are non-metallic materials that line the furnace shell (which is made of steel) and protect it from melting. Refractories have a limited service life and need to be replaced periodically. Proppane gas and oxygen are used to generate heat inside the EAF. Proppane gas is also needed to heat up the LF before the molten steel is poured into it and also heat up the tandish, which is a container that transfers the molten steel from the LF to the CCM. Lime is needed to Lime is used to remove phosphorus, sulfur, silica, and manganese from the molten steel.

break (jumps) in production is associated with the downtimes. We will use these breaks to impute productivity gains potentially associated with physical and managerial improvements.

For the period January 1997 to June 2001, we only have monthly data and hence cannot identify specific downtimes. Still, we can identify seven months during which plant utilization (the percentage of time during the month in which the melt shop was up and running) was substantially below the average plant utilization during the same calendar year.[12] This low level of plant utilization might indicate down times associated with investments. The relevant months are the following:

Table 3 – Potential downtimes, January 1997 – June 2001

Month	**Plant utilization during the month**	**Av. plant utilization during the calendar year**
Mar 1997	67.7%	78.4%
Sep 1997	61.4%	78.4%
Mar 1998	55.5%	79.7%
Oct 1998	58.7%	79.7%
Aug 1999	66.7%	86.2%
Feb 2000	79.2%	89.2%*
Sep 2000	73.1%	89.2%*

* December 2000 is a missing data

Using the daily data, from July 2001 onward, we identify the following periods during which the plant was down, we know the specific investment during a couple of event:

Table 4 – Production downtimes, July 2001 – September 2008

Period	**Type of investment**
Mar 17-27, 2002	Unknown
Jan 19-26, 2003	Replacing EAF Transformer
Jun 5-7, 2003	Unknown
Apr 19-22, 2004	Unknown
Mar 6-Apr 6, 2005	Replacing LF Transformer
Feb 4-13, 2007	Unknown

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[12] Plant utilization in these seven months was at least 10 percentage points below the average during the same calendar year. Using the same criterion perfectly identifies the months during the July 2001-September 2008 period for which we know of major shut downs from the daily data.

In March 2001, the steelmaker introduced a new incentive scheme, meant to boost worker productivity. The scheme was then gradually adjusted over the next few months and was finally instated on June 2001. Since then, the scheme was adjusted twice following major investments. The scheme is a group incentive program, based on the total daily output measured in tons of billets per hour.[13] Each day in which billets per hour is below some predetermined threshold, Q_0, the workers receive only a base salary. Above Q_0, the workers of all three daily shifts receive a bonus for each ton of billets above Q_0. The bonus is moderate for output levels between Q_0 and Q_1, and then it becomes steeper between Q_1 and Q_2. At Q_1 the bonus amounts to w_1. At Q_2 the bonus amounts to w_2, which also serves as a ceiling for the bonus payments. The incentive scheme is illustrated in the following figure:

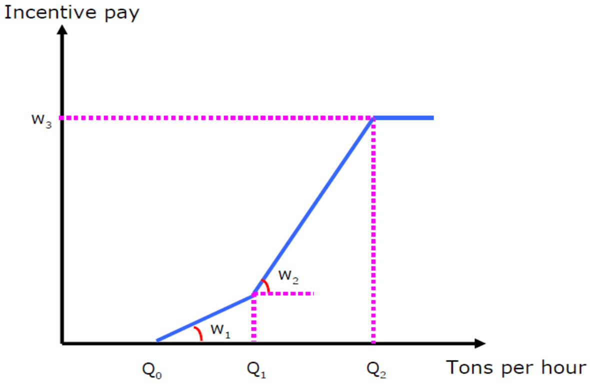

Figure 3: the steelmaker's incentive plan

The group incentive scheme is characterized by 5 parameters: Q_0, Q_1, Q_2, w_1, and w_2. As mentioned above, the parameters of the incentive scheme were adjusted twice following major investments. The following table summarizes the parameters of the incentive scheme, the changes in these parameters, and the reasons for the changes. Notice that while the incentive scheme changes were induced by physical improvements, the adoption was lagged by several months, potentially allowing the separate identification of the impact of each event.

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[13] Group incentives are common in minimills given the relative ease of measuring production-line and mill-level output and the difficulty of measuring individual employee contributions. Boning, Ichniowski, and Shaw (2007) study data on nearly all U.S. rolling mills operaing in steel minimill.and find that by the end of their sample period, group incentive pay plans are used by 91% of all rolling mills.

Table 5 – The incentive scheme

Date	Q_0	Q_1	Q_2	w_1	w_2	Event
June 1, 2001	18	20.5	24	20%	77%	New Incentive Model
March 1, 2003	19.75	22.25	25.25	17%	78%	EAF Transformer
July 1, 2005	21.5	24.5	27.7	19%	80%	LF Transformer

Finally, up to 2004, the melt shop operated the three daily shifts with 85 workers that were divided into three teams. As there was no reserve team, work load for the workers was very heavy (almost no vacations, many overtime hours). Starting from January 2004, the melt shop hired 18 new workers and introduced a fourth team which serves a backup. Following this change, the workers were organized in four teams of 26 workers each, rotating to cover the three daily shifts. In order to compensate existing workers for the drop in their overtime hours, the melt shop increased the hourly tariff of all senior workers by 17%.

5 Output Decomposition

We now look at the different elements of the output decomposition in (4).

5.1 Plant Utilization

Plant utilization reflects the percentage of time during a given month in which the melt shop was up and running. We compute it by dividing the actual plant hours during a month by the total hours in that month. Clearly, an increase in plant utilization is possible only if the steelmaker manages to cut the number and length of down times due to planned maintenance or unplanned disruptions.[14] The following figure presents the evolution of plant utilization over the sample period.

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[14] For example, the furnace shell (which is made of steel) is lined with refractories, which are made of non-metallic materials that can sustain high temperatures, to protect the shell from melting. Refractories need to be replaced periodically and this may cause delays. Moreover, due to wear, corrosion, and fatigue by either external damage or human error, the equipment in the melt shop has to go through periodic service maintenance which require downtimes.

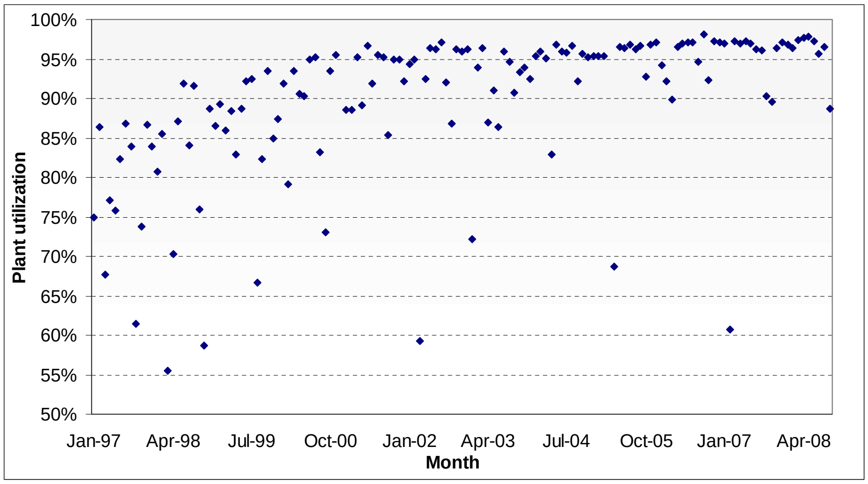

Figure 4: Plant utilization - actual plant hours divided by the total hours in a month, January 1997 - September 2008

Figure 4 shows that plant utilization increased gradually over the 1997 – 2001 period. Average plant utilization was 79.1% from January 1997 to December 1998, 89.3% from January 1999 to December 2001, and 93.4% from January 2002 to August 2008 (excluding March 2005).

Interviews with the steelmaker's management reveal that the increase in plant utilization between 1997 – 2001 was achieved by reducing the down times needed for planned maintenance from one day a week in 1997 to about 8 hours every two weeks today, and by reducing the number and length of unexpected delays. The later was done in part by giving workers more freedom in deciding how to handle problems.[15] In the Appendix we show figures that illustrate the evolution of some delays and problem over the period August 2001-September 2008. The main message from the figures is that the melt shop found ways to cut some delays and problems but other delays and problems have increased with the extent of plant utilization which is perhaps unavoidable.

5.2 Heats per Effective Day

Effort, and better coordination, may lead to more heats per unit of time. The next figure shows the evolution of the variable heats per –effective– day (24 hours of operation, so that this measure is not affected by changes in utilization) over the sample period:

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[15] Before the melt shop was acquired by the current owner, management was very centralized and workers tended to seek the CEO's advice on how to deal with unexpected problems in the production process.

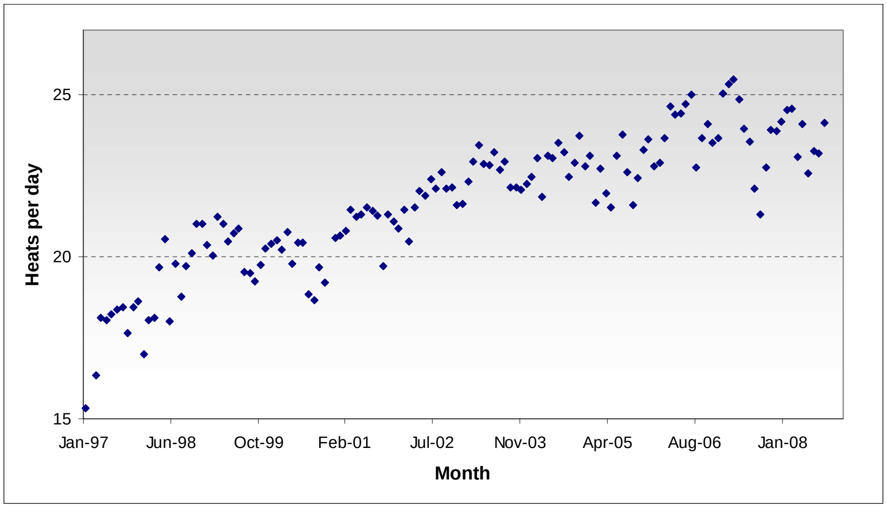

Figure 5: Monthly average of heats per day January 1997 – September 2008

The number of heats per effective day rose quite sharply from a little over 15 heats per day at the beginning of 1997, to around 25 heats per day towards the end of the sample period. The increase is gradual and steady, but unlike plant utilization, it is apparent throughout most of the sample.

5.3 Billets per Heat

Finally, better capital utilization or physical improvements may contribute to more billets per heat.

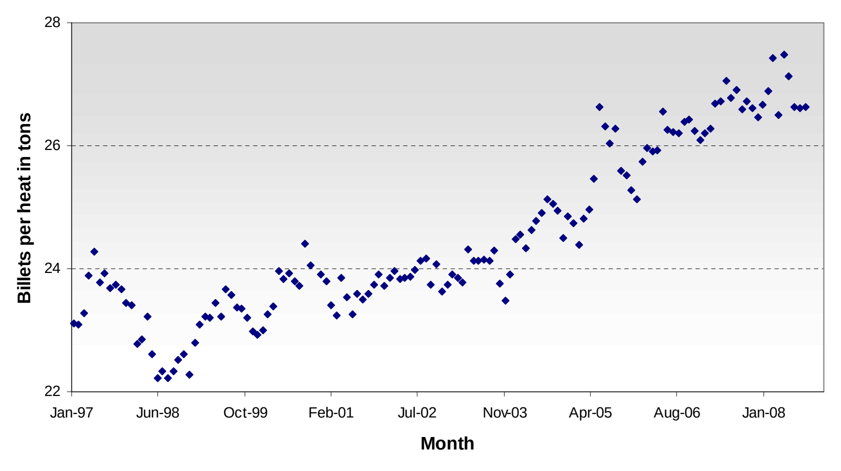

Figure 6: Monthly average of billets per heat in tons, January 1997 – September 2008

Figure 6 shows that the output of billets per heat cycle rose sharply over the sample period from about 23 tons per heat, early in the sample, to well over 26 tons per heat by 2008. A gradual but steady increase is apparent from 2003 to 2008, with a possible jump mid 2005.

5.4 Summary

To summarize the picture presented in Figures 4-6, the following figure shows annual numbers. They provide a smoother presentation of the trends in the data.

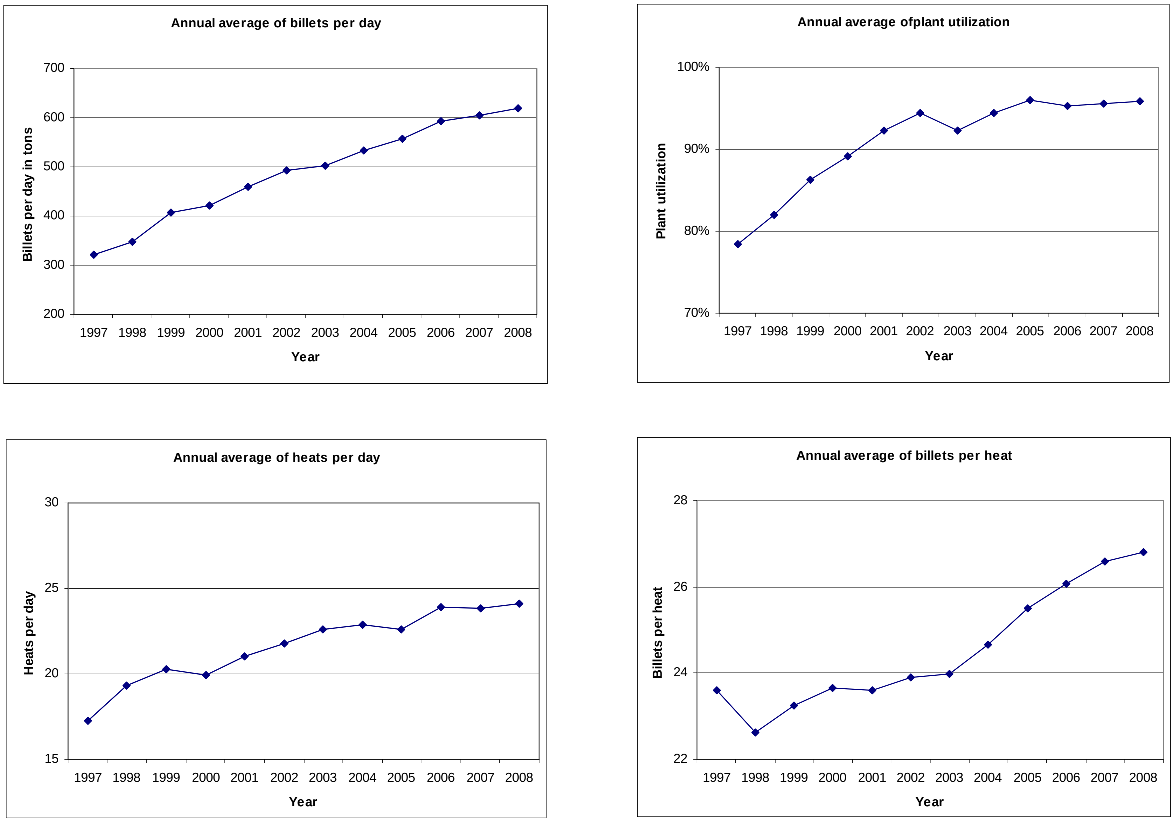

Figure 7: Annual averages of billets per day, plant utilization, heats per day, and billets per heat, January 1997 – Septmeber 2008

In the next figure we compute for each year the standard deviation from one month to another of billets per day, plant utilization, heats per day, and billets per heat.

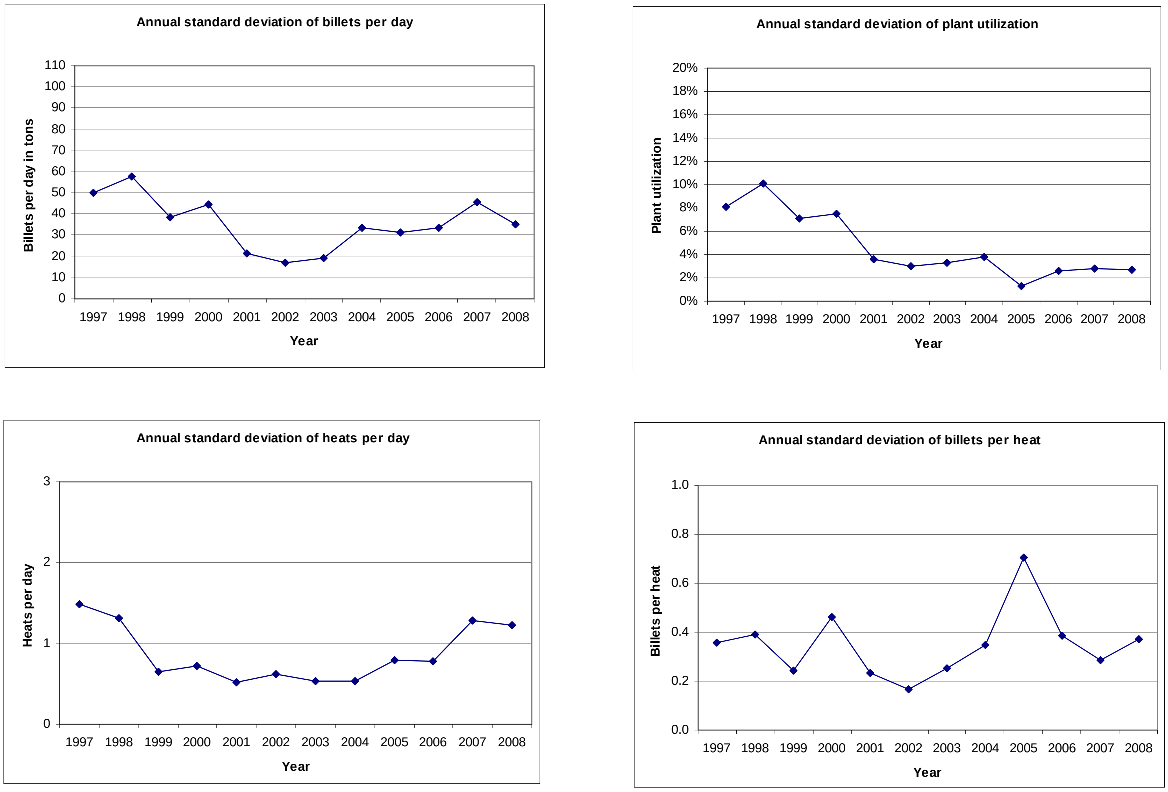

Figure 8: Annual averages of billets per day, plant utilization, heats per day, and billets per heat, January 1997 – September 2008

It is easy to see that after 1998, the melt shop became very consistent in terms of plant utilization: the standard deviation falls from about 10% in 1998 to around 3% from 2005 onwards. By contrast, we do not see a decrease in the standard deviation of heats per day or billets per heat.

The conclusion from Figures 4-8 is that prior to 2001, most of the gain in y_t comes from better plant utilization, i.e., increase in U_t. Following 2001, most of the productivity gains arise from increases in the number of heats per day, h_t, and billets per heat, y_h.

6 Sources of Productivity Gains

We now relate the evolution of each of the output components, U_t, h_t and y_h, to the events described in Section 4.2. The goal is to look for breaks that may point out which of the potential investments and incentive scheme –changes– may be responsible for the productivity gains in plant hours, heats per day, and billets per heat, respectively. We look for breaks by regressing each component on the critical dates. The critical dates for the incentive dummies are taken from Table 5. The next two tables present estimates for the period Jan 1997 - June 2001 using monthly data, and the period July 2001 - September 2008 with the daily data. In Table 6, the dummies associated with the various dates take the value 0 up to and including the relevant month and take the value 1 from the following month onward. For instance, the Sept 1997 dummy takes the value 0 up to and including September 1997, and takes the value 1 from October 1997 onward. Likewise, the dummies in Table 7 take the value 0 up to and including the relevant date, and take the value 1 after that date. For instance, the dummy Mar 17-27, 2002 takes the value 0 up to and including March 27, 2002, and takes the value 1 from March 28 onward.[16]

Table 6 – Regression results, January 1997 – June 2001

Monthly data

Dependent Variable	Plant hours		Heats per day		Billets per heat	
	Coeff	t-stat	Coeff	t-stat	Coeff	t-stat
Mar 1997	8.82	0.23	2.30	3.81	0.57	1.7
Sep 1997	−26.57	−0.79	−0.32	−0.6	−0.45	−1.56
Mar 1998	−9.93	−0.29	0.99	1.88	−0.94	−3.24
Oct 1998	−3.03	−0.08	0.71	1.25	0.53	1.71
Aug 1999	−29.58	−0.83	−1.50	−2.71	0.07	0.23
Feb 2000	−2.00	−0.06	−0.24	−0.45	0.50	1.72
Sep 2000	−33.31	−0.92	−0.16	−0.28	0.08	0.25
Incentive	−28.12	−0.59	0.48	0.65	−0.28	−0.69
Trend	4.13	1.24	0.07	1.42	0.00	0.15
Constant	563	18.33	15.09	31.68	23.24	88.3
R^2	0.43		0.85		0.64	
N	46		46		46	

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[16] The only exception is the Mar 6-Apr 6, 2005 dummy: although the melt shop resumed operations on April 7, 2005, it returned to full capacity only on April 10, 2005. Hence, the dummy takes the value 0 up to April 9, 2005, and takes the value 1 only from April 10, 2005, onward.

Table 7 – Regression results, July 2001 – September 2008

Daily data

Dependent Variable	Plant hours		Heats per day		Billets per heat	
	Coeff	t-stat	Coeff	t-stat	Coeff	t-stat
Mar 17-27, 2002	0.17	0.49	1.03	4.45	−0.29	−1.40
Jan 19-26, 2003	0.07	0.11	0.16	0.38	−0.03	−0.08
Jun 5-7, 2003	0.61	1.37	−0.53	−1.84	0.11	0.43
Apr 19-22, 2004	0.16	0.47	0.52	2.35	0.45	2.27
Mar 6-Apr 6, 2005	0.31	0.66	−0.93	−3.05	0.79	2.88
Feb 4-13, 2007	−0.01	−0.02	0.25	0.98	−0.05	−0.24
Incentive 1	−0.77	−1.04	0.93	1.96	−0.36	−0.84
Incentive 2	−0.41	−0.87	1.56	5.14	−0.28	−1.04
Trend	0.00	0.42	0.00	−0.19	0.00	3.89
Constant	22.36	88.3	20.90	120.4	23.23	149.1
R^2	0.01		0.13		0.26	
N	2570		2530		2545	

Plant Utilization Although figures 4 and 7 show a gradual increase in plant utilization, at least until 2001, none of the dummy variables in the plant hours regression in Tables 6 and 7 is significant. This implies that plant hours are not explained by any physical improvement, or the adoption and changes of the incentive scheme in either sample. This result persists even after dropping the trend from the regressions (not reported). The trend, borderline insignificant in Table 6 becomes significant after dropping the event dummies.

Heats per day Heats per day trend up during the first part of the sample (the 1997−2001 period), but not during the second part (the 2001 – 2008 period). Moreover, heats per day do not seem to be affected by the adoption of the incentive scheme during the first part of the sample, but are affected by the two changes in the incentive scheme during the second part. In other words, productivity responded to the adjustment of the parameters of the incentive scheme. Heats per day are also positively affected by two physical investments (Mar 17-27, 2002 and Apr 19-22, 2004), negatively affected by two investments (Jun 5-7, 2003 and Mar 6-Apr 6, 2005), and is not significantly affected by the two remaining investments (Jan 19-26, 2003 and Feb 4-13, 2007)

At least in the case of the Mar 6-Apr 6, 2005 dummy, which reflects the installation of a new LF transformer, the decline in heats per day seems plausible: an increase in either k_{LF} or a_{LF} apparently enabled melting more scrap per heat, which is expected to take longer. Indeed, the Mar 6-Apr 6, 2005 dummy is also positive and significant in the billets per heat regression, showing a larger production capacity in turn associated with longer time to melt.[17]

Billets per Heat Billets per heat show an upward trend in the second part of the sample, but this trend is economically very small. Billets per heat are unaffected by the introduction of or the changes in the incentive scheme, though it is positively affected by the investments in Mar 1997, Oct 1998, Feb 2000, Apr 19-22, 2004, and Mar 6-Apr 6, 2005 (the installation of the new LF transformer), and is negatively affected by the investment in Mar 1998. Interestingly, the Mar 1998 event is also associated with a positive effect on heats per day.

Learning by Doing vs Tweaking Learning by doing refers to the beneficial effect of accumulated knowledge on productivity (Arrow, 1962). Such knowledge is typically modeled as driven by accumulated past output (e.g., Benkard 2000, Thompson, 2001). We now examine whether productivity gains are indeed associated with past accumulated output, or whether they are is due to learning from experience, which is not necessarily related to accumulated production.

To this end, we define experience in period t as the accumulated output up to period $t-1$:

$$e_t = \sum_{\tau=1}^{t-1} y_\tau .$$

We regress monthly output y_t, on e_t, as well as on all the events reported in Tables 6 and 7. We use monthly data for the entire sample period, since it is unlikely that the melt shop can learn on a daily basis. Similarly, we define experience of each of the three components of output (plant hours, heats per day, and billets per heat) as follows,

$$e_t^c = \sum_{\tau=1}^{t-1} c_\tau , \qquad c_t = y_h,\ h_t,\ U_t,$$

and regress each of the three components, using monthly data on e_t^c, as well as on all the events reported in Tables 6 and 7 (the timing of investments and the introduction and adjustment of the incentive scheme).

Tables 8 and 9 below report the results of the four regressions, with and without time trend. For the sake of brevity, we do not report the coefficients on the various events as we are mainly interested here in the effect of experience on output and its components (the events are just used as controls).

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[17] The event is associated with the main jump in scrap, gas and oxygen per heat (and gas and oxygen per billet) during the sample, suggesting that more is melted, perhaps for a longer time (see graphs in the Appendix).

Table 8 – Regression results on the effect of experience on billets per day and its decomposition to components

January 1997 - September 2008, Monthly data

(t -statistics are in parenthesis)

Dependent Variable	Billets per day	Plant Hours	Heats per day	Billets per Heat
Experience	−0.02	−0.06	−0.03	−0.001
	(−2.29)	(−2.19)	(−2.26)	(−0.15)
Trend	13.73	42.67	0.63	0.05
	(2.57)	(2.22)	(2.29)	(0.41)
Event dummies	Yes	Yes	Yes	Yes
R^2	0.91	0.53	0.88	0.95
N	127	127	127	127

Table 9 – Regression results on the effect of experience on billets per day and its decomposition to components without trend

July 2001 – August 2008, Monthly data

(t -statistics are in parenthesis)

Dependent Variable	Billets per day	Plant Hours	Heats per day	Billets per Heat
Experience	0.003	0.001	0.000	0.001
	(2.41)	(0.81)	(0.56)	(4.75)
Trend	No	No	No	No
Event dummies	Yes	Yes	Yes	Yes
R^2	0.91	0.51	0.88	0.95
N	127	127	127	127

Tables 8 shows that experience does not help explain the growth in the melt shop's output or the evolution of three components: the coefficients of the experience variables are negative in all four regressions, rather than positive as a learning by doing would predict. Table 9 shows that once the trend is removed, the coefficients of the experience variables become positive, as experience captures the omitted trend. However, under learning by doing, accumulated experience should explain more than a trend. Deviations from the trend in experience, should be associated with above trend performance. It is clear from Table 8 that is not the case.

In sum, the evidence is consistent with the reports from managements, that productivity gains were the outcome of trail and error, or tweaks in production, rather than a function of accumulated production.[18]

7 Decomposing Productivity Gains

We now use the estimated coefficients of the previous regressions to impute the changes in plant utilization, heats per day, and billets per heat, which can be associated with the various events. The coefficient of each dummy represents the gain at the time of the event. By adding all dummies, which we found significatively different from 0, we impute all the gains in productivity associated with the events described in Section 4.2. The remainder, or unexplained, output growth represents the productivity growth associated with other managerial activities.

In the next table we present the change in plant utilization, U_t, heats per day, h_t, and billets per heat, y_h, over our sample period.

Table 10 – The change in output components over the sample period: January 1997 - September 2008

	U_t	h_t	y_h
Average value Jan 1997 - Dec 1997	572	17.3	23.60
Average value Jan 2008 - Sep 2008	702	23.7	26.88
Difference	130	6.4	3.28
Difference in percentage terms	22.7%	37%	13.9%

Substituting the numbers in Table 10 in (4), we can now present the overall increase in billets per day over the sample period as follows:

$$(1 + dU)(1 + dh)(1 + dy) = 1.227 \times 1.37 \times 1.139 = 1.91. \tag{5}$$

Let's impute the gains associated with the different events. First, since no event explains the gains in plant utilization, all the 22.7% gain in U_t remains unexplained.

Second, of the total increase in h_t over the sample period, 2.49 heats per day, or 38.9%, are associated with the incentive scheme (the sum of the coefficients of two incentive dummies). The physical investments are associated with an increase of 1.87 heats per day, or 29.2% of the total increase. In total then, measured events explain 68.1% of the gains in heats per day.

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[18] The international price of billets shot up from the end of 2003 until 2008. While the higher price may explain an incentive to increase output, we did not include price in the previous regresssions since prices do not directly change output given inputs. Price may have induced more tweaking effort. Which is what we want to measure through unexplained output growth.

Finally, the incentive dummies do not have a significant effect on y_h. Adding all the significant coefficients of the physical investments in the billets per heat regression, we can attribute an increase of 1.90 tons in y_h to physical investments, out of the overall gain of 3.28 tons of billets per heat over the sample period; this represents 57.9% of the total gain in billets per heat.

It is interesting to note that the incentive scheme seems to have increased the speed at which heats are completed without affecting the output per heat, which is presumably affected by technical considerations rather than the workers' effort. The physical investments are associated with some positive and some negative impacts on both heats per day, and billets per heat. This suggests that some of the improvements expand capacity at the expenses of speed, while others might do the reverse.

In sum, the explained components amount to:

$$\underbrace{(1)}_{\text{Utilization}} \times \underbrace{(1+0.37\times 0.681)}_{\text{Heats per day}} \times \underbrace{(1+0.139\times 0.579)}_{\text{Billets per heat}} = 1.352,$$

or 35.2% increase in billets per day.

Of this increase,

$$\underbrace{(1)}_{\text{Utilization}} \times \underbrace{(1+0.37\times 0.389)}_{\text{Heats per day}} \times \underbrace{(1)}_{\text{Billets per heat}} = 1.144,$$

or 14.4% can be attributed to the incentive scheme, while

$$\underbrace{(1)}_{\text{Utilization}} \times \underbrace{(1+0.37\times 0.292)}_{\text{Heats per day}} \times \underbrace{(1+0.139\times 0.579)}_{\text{Billets per heat}} = 1.197,$$

or 19.7% can be attributed to physical investments.

The remaining 42% (= 1.91/1.35 − 1), which remains unexplained by the investments and the incentive scheme, represent an annual productivity growth of 2.9%.

Another way to measure productivity, is to look at the evolution of value added instead of gross output. We define value added, at constant prices, as:

$$VA = \overline{p}_y y - \sum_{i=1}^{n} \overline{p}_i x_i,$$

where y represents the output of billets, $\overline{p}_y$ is the average price of billets over the sample period, $x_1, \ldots, x_n$ is a vector of material and energy inputs, including scrap, electricity, Ferro alloys, Oxygen, Propane, Lime, electrodes and Carbon, and $\overline{p}_i$ is the average price of input i over the sample period. We use constant prices in order to ensure that value added reflects changes of physical units, as opposed to changes in the relative prices of inputs and output; for instance, if billet prices increased more than input prices, value added would increase for reasons which are unrelated to productivity. Value added increased by 59.43%, from the first to the last year of the sample.

We regressed VA on all the events. Interestingly, the events do not help explain the increase in VA, as the sum of the statistically significant coefficients on the events is small and negative. This is consistent with the events enabling the utilization of more materials and energy in production (through longer hours of operation and more heats per day), without changing the production yield (the ratio of billets output to scrap input). This is not surprising, since given the relevant production process, one would not expect more billets with the same scrap input.

Since capital and labor were more or less constant over the sample period (save for the events), we can think of the growth in VA as a measure of the evolution of capital and labor productivity. Loosely speaking, TFP can be defined as $VA/(\overline{p}_k K + \overline{p}_L L)$, where $\overline{p}_k K$ and $\overline{p}_L L$ are the values of capital and labor inputs, measured in constant prices. In our case, both K and L were fixed over the sample period (up to the events), so the evolution of VA can be interpreted as a proxy for TFP. The TFP gain, is in the similar range as the output growth described above.

8 The incentive scheme

The incentive payments trended upward from around 35% of base salary in 2001, when the incentive scheme was just introduced, to around 60% towards the end of the sample period in 2008, although there is considerable variability around the trend (see Figure A2 in the Appendix). We found that the incentive scheme affected only heats per day. Interestingly, it did so only in conjunction with a technological improvement. The initial incentive scheme, instituted in June 2001, did not change productivity. Only the adoption of the two transformers, which was accompanied by adjustments in the parameters of the incentive scheme, seems to have affected productivity by increasing heats per day. As mentioned above, in total we can attribute a 14.4% output increase to the incentive scheme.

It is also worth mentioning that the incentive scheme rewards daily production, namely, the final bonus depends on the output of the three shifts working during the day. One could have expected group incentives, which are not associated with individual performance, and not even with the performance of a single shift (but rather all three shifts working during the day) to have little power. Instead they seem to work well. Conversations with the melt shop's management reveal that the main role of the incentive scheme is not moral hazard in the usual sense, but instead to induce the workers themselves to drive out weak workers who hold the entire group back.[19]

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[19] Quote from management: "As the 3 stages of melting - scrap melting, refinement, casting - are performed sequentially, there exists a strong downstream dependency among them. There is not so much a problem of free riding than one of weak links in the chain causing plant performance to deteriorate. We had such cases in the past and the group itself pushed those week links out - we think because of our efficient incentive scheme." Ghemawat (1995) discusses the effect of a similar incentive scheme at Nucor, which is a U.S. minimill operator and the largest steelmaker in the U.S. He concludes that, instead, the most important effect of the incentive scheme "seems to have been to create peer pressure for individual workers to exert themselves for the good of the group."

9 Discussion and Conclusions

This study documents the evolution of productivity in a firm operating in a traditional, mature, industry. Despite the absence of dramatic changes in the plant itself or the workforce, output increases gradually and continuously throughout the sample period. While an incentive scheme and some investments explain part of the gains in the different components of output, we are left with most of the gain unexplained. This gain is also not explained by cumulative experience, as one would expect based on standard learning by doing model. Moreover, the gain cannot be explained by R&D as the firm we study uses standard equipment which cannot be modified by the firm itself.[20]

Learning by experimenting, or "tweaking the production process," is the best explanation we gather from conversations with management. As it turns out, steel production in mini mills involves numerous trade-offs. For instance, using more refractories (non-metallic materials that line the EAF's shell and protect it from melting), allows the melt shop to run more heats before the refractories need to be replaced, but at the same time, it limits the amount of scrap that can be charged into the EAF, and hence the quantity of billets per heat. Likewise, using a longer electric arc allows the melt shop to reach higher temperatures inside the EAF and thereby speeds up the heat cycles, but may damage the refractories and requires the melt shop to replace them sooner (replacing the refractories requires a downtime). As a third example, charging more scrap into the EAF, increases the quantity of billets per heat, but can also raise the probability that the electrodes (that strike the electric arc inside the EAF) will break, in which case the melting process needs to be stopped until the electrodes are replaced. Finding the optimal balance between the various trade-offs requires a lengthy trail and error process that can be very slow, given that there are many variables that may affect the various trade-offs. Moreover, these variables differ across melt shops, even if they are all using the same equipment. The implication is that "learning how to use the melt shop optimally," or "tweaking the production process" is a slow process that involves numerous trade-offs and can take a long time.

Beyond their theoretical and empirical relevance, our findings imply that learning by doing is not simply a function of cumulative output and is not guaranteed automatically. Rather, it is the result of an active tweaking process. Of course, our results reflect the learning process at one particular plant, in one particular industry. In this sense, our study shares the issue of generalizability with most of the rest of the learning-by-doing literature. Nevertheless, we believe that our findings offer insights that can be cautiously extended to other production operations, particularly complex manufacturing processes. Further, even when direct extension is not warranted, the results can be used to direct future research on learning by doing.

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[20] In an interview, the steelmaker's CEO said "in the steel industry you cannot invent anything. You must use the equipment according to the manufacturer's specifications."

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10 Appendix

Work Hours and Wage Premium Total monthly work hours (regular work hours plus overtime) are presented in the following figure. We have data on monthly work hours only for a part of the entire sample period.

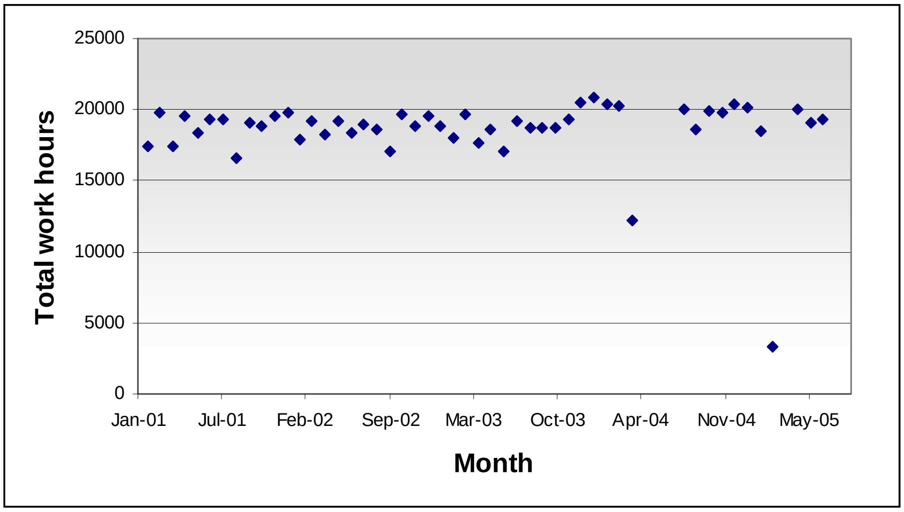


Figure A1: Total work hours, January 2001 - July 2005

The figure shows clearly that monthly work hours remained pretty much constant. It is interesting to note that during the period covered by the figure, the output of billets has increased from an average level of 13,957 tons per month in 2001 to an average level of 16,464 tons per month in 2005, which reflects an increase of 18% in output.

The following figure shows the total wage premium that was paid to workers above their base salary:

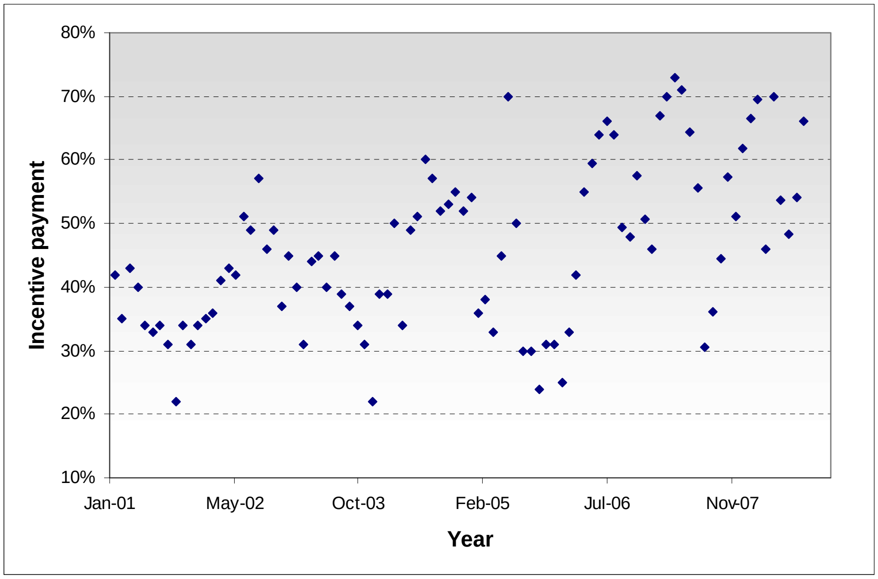


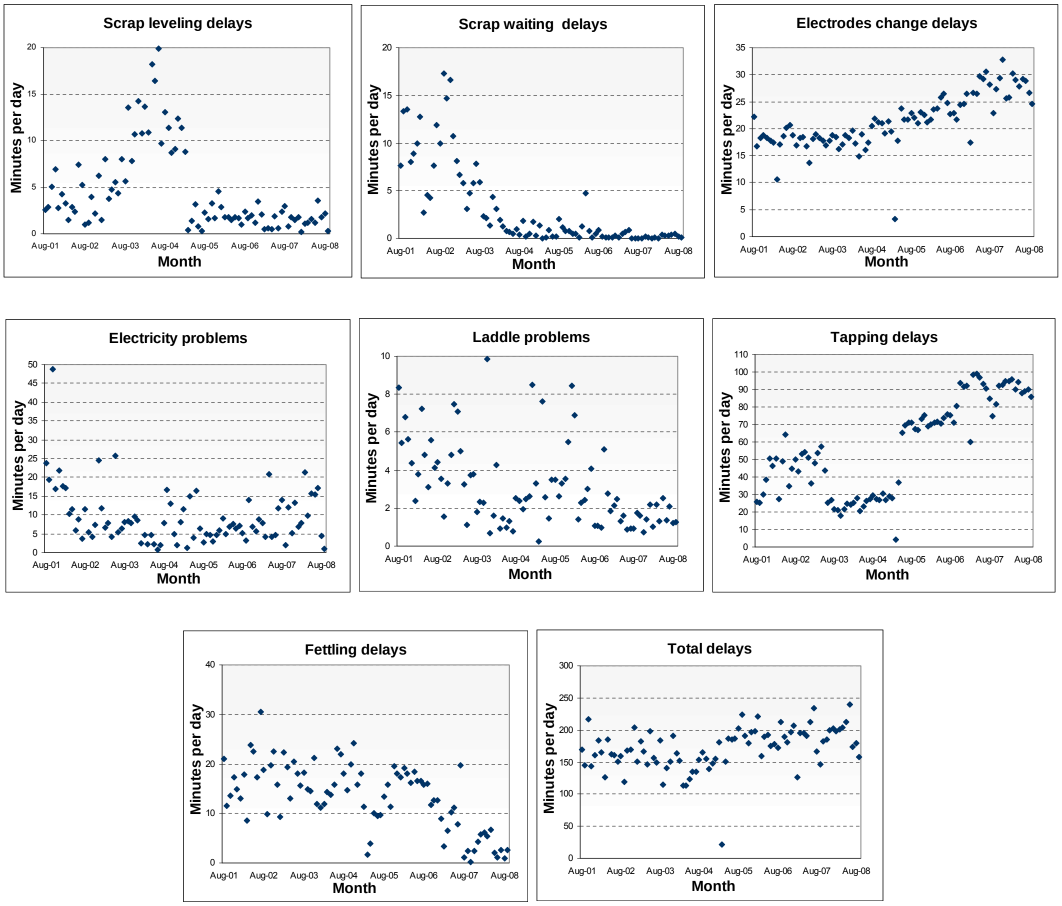
Figure A2: Wage premium paid to employees, 2001-2008

The figure shows an upward trend in incentive payments from around 35% of base salary in 2001, when the incentive scheme was just introduced to around 60% towards the end of the sample period in 2008, though there is considerable variability of incentive payments around the upward trend line. In fact, the standard deviation of incentive payments around their mean is 64% higher in $2005 - 2008$ than in $2001 - 2004$.

Profitability One may argue that a possible reason why we see increase in productivity is that the price of billets and rebars increased dramatically just before the global financial crisis in September 2008 and hence, the melt shop found it profitable to expand output while beforehand it did not work at full capacity not because it was unable to do that but rather because it did not find it profitable to do so. Interviews with the steelmaker's management reveal that was not the case: the melt shop was trying to operate at full capacity from the day the current owner acquired the melt shop at least until September 2008, and the only impediment to production expansion was the effective capacity of the melt shop, which was limited, but kept increasing over time in the way we document in this paper.

Still, one may wonder if production was profitable or not. To examine this issue, we compute the direct profitability of billet production, defined as the international price of billets as quoted in *Metal Bulletin*, times the monthly production of billets, net of the variable cost of billets, including the price of scrap, electricity, Carbon, Lime, Ferro alloys, etc (directly profitability is in fact similar to the concept of value added except that it is expressed in terms of current rather than constant prices). The computation shows that the direct profitability of billets production was positive until the eruption of the global financial crisis at the end of 2008. This finding is consistent with the management's claim that it was had an incentive to expand output as much as possible. The implication then is that the constraint on production was technical, rather than a deliberate restraint on output by management. The puzzle is how did the steelmaker manage to expand output, and given that this was profitable all along, why wasn't it done earlier.

Delays One of the important determinants of productivity are various delays and problems in the production process. In the following figure we present some of the delays and problems over the period August 2001- September 2001. The delays and problem that we report are in loading the scrap into the EAF (scrap leveling and scrap waiting delays), problems with electricity and electrodes, problems with the ladle furnace, delays when pouring the molten steel from the EAF to the LF (tapping delays), delays due to the need to repair damages to the refractories which line the EAF's shell and protect it from melting, and total delays.



Scrap leveling delays

Scrap waiting delays

Electrodes change delays

Electricity problems

Laddle problems

Tapping delays

Fettling delays

Total delays

Figure A3: Average delays and problems in minutes per day, August 2001-September 2008

The figure shows that delays due to feeding the scrap into the EAF were cut significantly in 2004. Electricity problems, LF problems, and fetling delays also show a decreasing trend although these trends seem to be less dramatic than the decrease in scarp related delays. On the other hand, the need to change electrodes led to increasing delays as production grew over time, and tapping delays also show an increasing trend with a temporary decrease in $2003 - 2004$. The final figure shows that total delays grew somewhat over time as production increased.