Essays on the Economics of the Aluminium Industry

Jerry Blomberg
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Abstract

This thesis consists of an introduction and five self-contained papers all dealing with various aspects of the economics of aluminium markets and production. **Paper I** focuses on various efficiency issues within the global primary aluminium industry. Using Data Envelopment Analysis (DEA) and data for the year 2003, we find that in general primary aluminium smelters are efficient given the scale of operation. However, many smelters operate with increasing returns to scale. Thus, many smelters would lower their average costs if the scale of production was increased. Furthermore, there exist substantial allocative inefficiencies in the industry, i.e., smelters are inefficient in changing the factor set up according to market prices. Overall, there are significant variations in the level of efficiency across smelter locations. Finally, we estimate the potential for factor reductions across smelter technologies and locations. **Paper II** analyzes the development in total factor productivity (TFP) over the period 1993-2003 in the global primary aluminium industry using DEA. The Malmquist indices calculated show that with the exception of Western Europe, smelters in high cost regions have experienced rapid TFP-growth, mainly driven by technical progress and not (as a priori assumed) by efficiency improvements. In regions with rapid capacity build-up, TFP-change is found to be weaker but likewise driven mainly by technical change. Finally, we do not find support for the notion that the dispersion of different smelter technologies affects regional smelter performance. Using a Translog variable cost function model, **Paper III** examines the *ex post* factor substitution possibilities in the primary aluminium industry in Western Europe and the Africa-Middle East region (AME) for the period 1990-2003. The results indicate higher short-run own- and cross-price elasticities at smelters in the AME region than in Western Europe, at least when it comes to labour and electricity demand. The results also suggest that in both regions the demand for electricity has over time become less sensitive to short-run price changes, while the substitution possibilities between labour and material have increased but only in the AME-region. The liberalization of the Western European electricity markets in combination with the rigid labour markets in this part of the world suggest that the shift in production capacity from the western world to the AME-region as well as China may continue. **Paper IV** provides an econometric analysis of the determinants of short-run supply and demand in the Western European market for secondary aluminium for the period 1983-1997. The empirical results indicate both price inelastic demand and supply. Policies aimed at increasing aluminium recycling by manipulating price will thus be ineffective considering the low own-price elasticity of secondary supply. However, increased demand for better fuel efficiency and safety in cars might increase the demand for materials with a favourable strength to weight ratio, such as aluminium, thus potentially increasing the demand for secondary aluminium. Finally, **Paper V** extends the analyzes in Paper IV by; (a) explicitly modelling the interdependencies between the primary and the secondary aluminium markets; (b) estimating secondary aluminium supply in a Cobb-Douglas framework; and (c) modelling aluminium scrap generation. The econometric results indicate that the secondary industry acts like a price taker to the primary aluminium industry. Taking account of the interdependencies between input and output prices in secondary aluminium production, we find inelastic supply responses, thus confirming the ineffectiveness of price-driven policies aimed at stimulating recycling. We further calculate a continuously growing stock of scrap. Increased availability of aluminium scrap raises the probability of secondary producers to find the wanted quality, thus lowering the cost of recycling. The impact on supply is however found to be small. Given that increased recycling probably must come from the stock, the low responsiveness of supply from increased scrap availability indicates that attempts to stimulate ‘mining’ of the scrap stock may be costly.
To Åsa, William and Alva
List of Papers

This thesis contains an introduction and the following papers:


Acknowledgements

More than a decade ago – I believe it was early spring time – I took a bus trip that, as it turned out, would impact my academic career greatly. During the trip, Professor Marian Radetzki asked me if I was interested in becoming a Ph.D. student in economics at Luleå University of Technology. He even gave me a choice of topics; Russian coal or metal recycling. After some profound soul searching I picked the latter topic – in reality mostly because I thought studying Russian coal mining sounded somewhat dreary and depressing. With the benefit of hindsight, I now know that explaining to a non-economist (and probably most economists too) why focusing on aluminium markets is much more fun than Russian coal is difficult. And still, after many and long detours, I have finally reached the final destination of that bus trip, and you now hold the result in your hands. So, read on and have fun!¹

Over the years, many individuals have provided invaluable advice, assistance and help without which this thesis never would have been completed. Marian Radetzki, aside from all the constructive criticism and supervision, most likely did wear out several pairs of good shoes kicking me “in the butt” to make me complete my Licentiate thesis, which today makes up parts of this thesis. Stefan Hellmer accompanied me in my travels searching for data, and taught me the value of “getting my fingers dirty” with the data and stop reading obscure journal papers. In the latter parts of my attempts to get me a Ph.D. degree, Patrik Söderholm and Bo Jonsson have had pivotal importance. Patrik has the eye of an experienced general for what can, need and should be done to overcome and prevail (i.e., to wrap up this thesis). Beside this, he has a (in my case much needed) gift and patience for language editing.² Bo, however packed his schedule ever was, always found time to explain for me for the umpteen time how some particular issue in DEA work or do not work. And even more importantly, he helped me with that big, glowing thing residing on my office desk (I believe they call it a computer).

Furthermore, I wish to thank all the past and present members of the International Advisory Board who assist the research at the Economics Unit and who all have provided invaluable advice in one way or another. They are; Professor Chris Gilbert, University of Trento, Professor John Tilton, Colorado School of Mines, Professor James Griffin, Texas A & M University, the late Professor David Pearce, University College London, David

¹ Be forewarned though; Professor Radetzki once remarked at a seminar treating the first paper in this thesis that it looked like “a solid paper, but OOOHHH so dull”.
² Even this particular sentence needed editing!
Humphreys, formerly at Rio Tinto Ltd, Professor Ernst Berndt, MIT and Professor Thorvaldur Gylfasson, University of Iceland. Here I also would like to take the opportunity to thank Professor Christian Azar, Chalmers University of Technology, who served as the discussant at my Licentiate seminar, and Professor Lennart Hjalmarsson, Gothenburg University, who provided invaluable comments at my trial thesis defense.

Of course there are also all the past and present colleagues at the Economics Unit. Thank you; Anna C, Anna D, Anna G-K, Anna K-R, Kristina, Christer, Robert, Linda, Olle, Thomas S, Thomas E, Mats, Eva, Fredrik, Gerd, Berith and Åsa. Not only have you provided constructive criticism and ideas for my research, but perhaps even more importantly, you have all contributed in making this workplace a place where I enjoy working. A special thank you to Staffan J, who once every fall opens up his sports cabin to feed (the enlightened parts) of the Economics Unit dumplings made from moose blood, with boiled liver and marrowbone. After such a meal and the mandatory sauna, I always feel strengthened to meet another semester of research.

In addition, the generous financial support from Forskningsrådsnämnden (FRN) and from Luleå University of Technology (Philosophy Faculty) is gratefully acknowledged.

Finally, I would like to express my unwavering love and gratitude to my wife Åsa, and my kids William and Alva. You constantly remind me what is really important in life - and however much this thesis will move and shake the research frontier – it is not this book! It is much more important to spend time constructing various LEGO-structures or trying to reach the next level in some video game! Without your support and presence, I would not have finished this journey. And to my parents and parents-in-law, thank you for your support. Without all the times you with short notice picked up the kids after school or kindergarten or provided cheap labour on some unfinished project on our house, the work on this thesis would have been seriously delayed.

Luleå, February 2007

Jerry Blomberg
INTRODUCTION

The overall purpose of this thesis is to analyze the economics of selected parts of the aluminium industry. While other major non-ferrous metals such as copper has a history going back some 9,000 years (Henstock, 1996), aluminium is a comparatively novel metal and was isolated for the first time in 1825. However, even after Hall and Héroult devised the electrolytic process in 1886, which still today remains the base technology for primary aluminium manufacturing, it was not until after World War II that mass production and use took off. Over the last thirty years, global aluminium production and consumption have seen average annual growth rates of 4-5 percent, which is considerably higher than the growth experienced in, for example, the copper market and most other major metal markets. As Figure 1 demonstrates, aluminium is today (2003) the single most important non-ferrous metal with an annual consumption of close to 32 Mtons, approximately twice that of copper.

![Figure 1. Global Production and Consumption of Aluminium 1970-2003](image)

Aluminium use has not only expanded in tonnage; the number of applications where aluminium is used has also soared. From being an exclusive metal, used in for example military applications, aluminium has now penetrated the mass consumption market as well. This development has to some extent been driven by the many favorable qualities of aluminium, such as low specific gravity, good corrosion resistance, high electrical and

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1 For example, at the court of emperor Napoleon III of France n the mid-19th century, only the privileged few was allowed to use cutlery made from aluminium, while the others had to make do with silver and gold plates, spoons and forks. (Henstock, 1996)
thermal conductivity and an ability to be alloyed with other metals and cast, rolled, pressed and extruded into many shapes and forms. These characteristics have enabled aluminium to successfully compete with other metals such as iron and steel in auto applications, copper in electrical transmission and tin and steel in beverage and food containers.

A second development regards the increased recovery of scrap aluminium, which has more than tripled on a global level (see Figure 1). By the beginning of the new millennia, aluminium produced from scrap metal supplied approximately a quarter of the aluminium consumed, up from 17 percent in the beginning of the 1970s. However, recycled aluminium has in some regions and nations come to overtake the primary industry in production terms and have become a major downstream supplier of metal.

This thesis will examine the economics of the two main parts of the aluminium industry, i.e. manufacturing of aluminium from primary material (primary aluminium) and from scrap (secondary aluminium). In the first part particular attention will be paid to three main issues, namely the level and variation of efficiency of primary smelters, the development over time of their productivity and lastly the existence and extent of factor substitution in primary aluminium smelting. In the second part, factors determining supply and demand of secondary aluminium made from recycled scrap will be identified and measures of scrap accumulation developed. As will be show below, these general research topics deserve detailed scrutiny with economic methods.

DELINEATION OF THE STUDY AND OVERALL RESEARCH PROBLEMS

The key stages in the production of aluminium are summarized in Figure 2. There are two main sources of raw material from which aluminium metal are produced; bauxite ore and scrap aluminium metal. Bauxite ore is refined into aluminium oxide (alumina) by the Bayer process in an alumina plant before being shipped to a primary aluminium smelting facility. In the primary aluminium smelter, the alumina is further refined using the aforementioned Hall-Héroult electrolytic process of which there are two varieties, the Soderberg- and the Prebake processes. The output of primary aluminium smelters, ingot products such as slabs, billets, casting alloys and remelt ingots, are used by intermediate producers of various cast and wrought products.

The other source of raw material - scrap metal - comes in two general varieties, old and new scrap. Old scrap arises when products containing aluminium metal are worn out and subsequently discarded. New scrap arises during all stages in the manufacturing process itself;
examples are borings, clippings and trimmings which is fed back into the production process and remelted once more into marketable qualities of aluminium.

This thesis consists of five self-contained papers in two distinct parts, dealing primarily with the sections of the aluminium industry found in the bold boxes in Figure 2. Specifically, the first part of the thesis focuses on the on the production of primary aluminium at primary aluminium smelters, while the second part focuses on the supply and demand of secondary aluminium from secondary refiners. The selection of these sections of the industry can be motivated for a number of reasons.

**Issue Concerning the Primary Aluminium Industry**

Beginning first with the primary aluminium smelting industry, this sector has experienced some dramatic changes over the decades. Back in the beginning of the 1970s, primary smelters in North America, Western Europe and Asia (at the time almost entirely made up of Japanese smelters) among them shared almost three quarters of the global market in production terms (see Table 1). The primary aluminium industry in these regions supplied a huge downstream industry with metal. Thirty years later, however, these regions barely maintain 40 percent of global production, and the decline is not only in relative terms. This development is at least to some extent driven by the vast energy requirements of the Hall-Héroult electrolytic process, making the aluminium smelting industry vulnerable to changes in electricity prices. For instance, in the aftermath of the oil price shocks in the 1970s, the Japanese primary aluminium industry, once the second biggest in the world as almost entirely
dismantled over the course of a few years in the 1980s (e.g., Goto, 1988). More recently, significant capacity closures have occurred in the US, partly driven by increasing energy costs. The western European primary industry is also under strain, with threatening capacity closures mainly in the central part of the region under way (e.g., Fischer, 2006; Commission Staff Working Document, 2006). New smelter capacity has instead been installed in “untraditional” locations such as Africa and the Middle Eastern region, Latin America and more recently there has been a remarkable expansion of production capacity in China, making it the world leader in production terms by 2003. Moreover, the substantial aluminium industry in the CIS-countries has come to be more integrated into the global primary aluminium market.

Table 1. Regional Share of World Primary Aluminium Production, 1970-2003

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<tbody>
<tr>
<td>Western Europe</td>
<td>0.196</td>
<td>0.235</td>
<td>0.203</td>
<td>0.164</td>
<td>0.156</td>
</tr>
<tr>
<td>Eastern Europe</td>
<td>0.036</td>
<td>0.029</td>
<td>0.020</td>
<td>0.016</td>
<td>0.015</td>
</tr>
<tr>
<td>North America</td>
<td>0.444</td>
<td>0.358</td>
<td>0.292</td>
<td>0.248</td>
<td>0.200</td>
</tr>
<tr>
<td>Latin America</td>
<td>0.016</td>
<td>0.051</td>
<td>0.093</td>
<td>0.089</td>
<td>0.083</td>
</tr>
<tr>
<td>Oceania</td>
<td>0.020</td>
<td>0.029</td>
<td>0.078</td>
<td>0.086</td>
<td>0.080</td>
</tr>
<tr>
<td>Africa &amp; Middle East</td>
<td>0.020</td>
<td>0.038</td>
<td>0.055</td>
<td>0.092</td>
<td>0.078</td>
</tr>
<tr>
<td>USSR/CIS</td>
<td>0.165</td>
<td>0.151</td>
<td>0.183</td>
<td>0.149</td>
<td>0.143</td>
</tr>
<tr>
<td>Asia</td>
<td>0.091</td>
<td>0.086</td>
<td>0.033</td>
<td>0.041</td>
<td>0.043</td>
</tr>
<tr>
<td>China</td>
<td>0.017</td>
<td>0.022</td>
<td>0.044</td>
<td>0.115</td>
<td>0.202</td>
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The changing geographical structure of the primary aluminium industry is to some extent explained by shifts in relative input costs (Nappi, 1992). The locational factors include; (a) the level and variability in factor cost, of for example, labour and most prominently for aluminium smelting, electricity; (b) the presence and quality of economic infrastructure and institutions; and (c) the legacy of past investments. However, competitiveness has also been affected by public policy. As energy is vital to the industry, the cost of energy has not surprisingly been altered by public policies over the years in many regions. These policies have aimed at capturing benefits from abundant local energy sources by either granting short-term discounts in order to lure investments, and/or varities of variable and preferential long-term contracts to primary smelters (Ibid.). Examples of countries where such discount has been granted to primary aluminium smelters include Australia, Brazil and Canada. The development of primary smelting capacity in the Middle East region is also partly driven and supported by public authorities searching for ways to use their abundant energy sources to differentiate the region’s industry. Long term contracts have also been granted in parts of
Western Europe (Commission Staff Working Document, 2006). Another example of policy intervention is the general support levied by local/regional Chinese authorities, sometimes in opposition to the central government, to the development of smelter capacity in order to accelerate regional economic development (CRU, 2004). The regional shift in production capacity has also been affected by the rapid economic growth in, for example, China, driven by massive infrastructural and industrial developments giving rise to increasing demands for metals and the potential to develop a national aluminium industry. This relative shift of capacity from locations in the West, with relatively well functioning market economies and, due to a long legacy of aluminium production, assumedly experienced management and technical staffs to new, “untraditional” locations raise a number of questions.

Differences in factor costs across regions are perhaps the most important determining force affecting competitiveness; however, they are not the only determinant. In economics a common assumption is that firms strive to maximize profits which, under competitive conditions, imply that resources will not be wasted. To behave optimally, firms have to be efficient in a technical or engineering sense, i.e., they should use the minimum amount of production factors that is technically feasible to meet the market demand. More importantly from an economic theory standpoint, firms are also required to minimize the cost of production, i.e., to optimally allocate the input resources in accordance with their prevailing market prices. Over time, competitive pressure and the strive for profit may ensure that firms will become ever more efficient either by becoming better at what they do with their existing technology, or by introducing new, cost saving technologies and management practices. However, in practice firms rarely achieve full efficiency in resource use. Market distortions, government interference, management incompetence and incomplete information make at least some firms and production units deviate from what constitute best practice in a given industry. Such departures can either create a competitive disadvantage even if factor costs might be competitive in a certain location or aggravate already existing cost disadvantages.

Several authors point to significant efficiency slacks in heavy, capital intensive process industries, including for the iron and steel industry Ma et al. (2002), Zhang and Zhang (2001), Ray et al. (1998), Wu (1995 and 1996), Ray and Kim (1995), Kalirajan and Cao (1993) and Gruver and Yu (1985), and for the paper and pulp industry Lee (2005) and Yin (1999, 2000). In short the above studies point to the potential for efficiency improvements but also to variations in the level of efficiency across regions, especially concerning the ability to respond effectively to market signals. Such ability has critically to do with the expertise of management and the institutional structure at a certain location, where the latter may be less
adequate in many new, developing economies than in the mature market economies in the west.

However, harnessing potential efficiency gains depends critically on the potential to change factor set ups. Primary aluminium production is often claimed to be characterized by a putty-clay technology, where factor set up is largely determined *ex ante* the investment decision (e.g. Bye and Førsund, 1990; Førsund and Jansen, 1983). If this characterization is true, improvements in efficiency and thus competitiveness can only come from undertaking major investments, while short run improvements by adjusting factor use is close to impossible. Other authors such as Larsson (2003) and Lindquist (1995) however show the existence of limited substitution possibilities even in the short run. Thus, there is a need to establish the potential for factor substitution, especially in the parts of the world which are loosing ground in the global competition (e.g., Western Europe).

Given the ongoing geographical shift there is also a reason to investigate whether there are differences in efficiency and the ability to meet changing market conditions across regions of locations. For example, as smelters in the west seem to be under increasing pressure and with threatening closures and loss of output shares, they should have more to benefit from improving efficiency, productivity and being apt to change factor use then smelters in new locations. Thus, in the first part of the thesis three general questions concerning the primary aluminium industry will be raised. *First*, to what extent is the global primary aluminium industry efficient and if not so, what kind of inefficiencies are there and what must be done to alleviate possible inefficiencies? *Second*, what is the short-run potential for factor substitution, and *third*, how have the above developments affected industry productivity over time? In addressing these questions we also raise further auxiliary questions.

In conducting the analysis we will take into account the ongoing technological shift from one type of smelter technology to another in the primary aluminium industry, namely from Soderberg to Prebake technology. This development has its roots in the latter technology’s claimed better energy and environmental performance. However, substantial Soderberg capacity remains and in certain locations such as China and the CIS region it is the major technology applied. Thus, we will focus on potential efficiency and productivity differences across technologies to gain further insight into any regional variations in efficiency and productivity.
Issues concerning the secondary aluminium industry

The costliness of virgin extraction and primary aluminium production in combination with the virtually indestructibility of aluminium once produced, makes scrap recovery and recycling of aluminium a usually profitable enterprise (Henstock, 1996). Thus, markets for scrap material have existed almost as long as aluminium has been used. The assertion that markets for recycled metals in general and aluminium in particular will arise - regardless of policies aimed at stimulating recycling - raises a number of questions. What factors determine the amount of metal supplied from scrap, and what is the economic significance of each of these factors? What determines the demand for products made from scrap metal, and how does the market for metals made from scrap interact with the market for primary metals? The proper understanding of such questions is important, not the least because of the increased interest from public policy makers concerning recycling in general. In many ways, recycling has come to be viewed as a key element in a sustainable society (Henstock, 1996). Alleged benefits of recycling include extension of resource life (when considering a non-renewable resource such as minerals), reduction in the need for landfill space and energy conservation (Ibid.). These and other benefits are often assumed to outweigh the private and social cost of recycling and therefore increased recycling is seen as a worthy social goal. This partly explains the manifold of policies aimed at stimulating recycling, such as mandatory deposit schemes and subsidized recycling infrastructure. However, whatever claim, well founded or not, that is made about the socially desirability of metal or other materials recycling activities, knowledge about the market in question is important for the formulation of efficient policies.

The existence of markets for secondary aluminum (at least if we neglect trade) presupposes prior production and consumption. Thus, it is only naturally that it is in the mature economies in Western Europe and North America with a long history of aluminium consumption and production, the most substantial aluminium recycling industries is found. As consumption of aluminium-containing goods accumulates over time, so will the potential for scrap recovery. As was noted above the sources of supply to meet the increased aluminium demand has changed somewhat over the decades. Up until the mid 1970s the Western European primary aluminium industry grew rapidly, partly fuelled by subsidized electricity rates. When the oil shocks of the 1970s hit the Western World with higher energy costs this

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2 Not all agree on the social desirability of recycling. See, for example, Radetzki (2000) for a critical analysis of the social costs of the recycling of packaging waste in Sweden.

3 See Kirchner (1988) for a thorough analysis of the European primary aluminium industry’s development up until the 1980s.
growth was halted, and European primary production levelled off in the 1990s. The decrease in the competitiveness of European primary production had two effects. The first was a relocation of primary production capacity to countries with low energy costs (as illustrated above). The second was an increase in the relative competitiveness of the secondary aluminium industry due to the significantly lower energy requirements of smelting and refining scrap compared to primary production. As primary production growth in Europe came to a halt, the role of recycled aluminium in ‘domestic’ European supply over time became more important. As Table 2 shows scrap recovery in Western Europe now stands for more than 27 percent of aluminium consumption and the industry’s output is more than three fifths of the primary industries. In some countries in Western Europe, such as Italy, the role of the secondary industry now overtakes that of the primary aluminium industry (OEA, 1998).

**Table 2.** Primary Aluminium Production and Aluminium Scrap Recovery as Shares of Aluminium Consumption in Western Europe, 1970-2003

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<tr>
<td>Primary Production as a Share of Consumption</td>
<td>0.602</td>
<td>0.745</td>
<td>0.57</td>
<td>0.443</td>
</tr>
<tr>
<td>Scrap Recovery as a Share of Consumption</td>
<td>0.243</td>
<td>0.243</td>
<td>0.258</td>
<td>0.271</td>
</tr>
<tr>
<td>Scrap Recovery as a Share of Primary Production</td>
<td>0.404</td>
<td>0.326</td>
<td>0.453</td>
<td>0.611</td>
</tr>
</tbody>
</table>


Before proceeding, some delineations need to be emphasized. The aluminium recycling industry consists in broad terms of secondary refiners, producing cast alloys and secondary remelters, producing wrought alloys (see Figure 2). In the cases where the refineries and remelters do not supply themselves they are supplied by independent metal merchants, collecting and processing a vide variety of metal scrap on an industrial scale. Throughout this thesis we will concentrate our analysis of aluminium recycling on the secondary refinery industry.

The reason for limiting the analyses to the refinery industry is that secondary refiners are the bulk users of scrap from retired products, so called post-consumer or old scrap. Recycling of old aluminium scrap is important from a policy perspective since it alleviates depletion and landfill scarcities. It is also usually more sensitive to fluctuations in costs and prices. The other main type of scrap, new or production scrap, arises during manufacturing and is usually recycled immediately. Recycling rates for new scrap are normally close to 100 percent. The availability of new scrap is thus closely linked to production and overall

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4 Secondary smelting demands down to 5 percent of the energy requirements needed in primary aluminium production (Henstock, 1996).
consumption levels of aluminum, and increases in scrap prices may change the supply only in a minor way. In addition, a significant share of the new scrap ‘produced’ never enters the market but is recycled ‘in-house’ in the production facility itself, and it does therefore not have a market price tag. Contrary to new scrap, a rise in old scrap prices or a decrease in recycling costs might induce greater amount of recycling of old aluminium scrap, since parts of what is scrapped every year is not recycled immediately but is left in junk yards, landfills etc. When margins increase for secondary refiners, it becomes profitable to ‘mine’ this stock of scrap, thus increasing the supply based on old scrap. On the output side the main product of secondary refiners, casting alloys, has less rigorous quality demands than do wrought products. Wrought products such as sheets and extrusion bars, if made from scrap, demand virtually pure material of known composition. This almost entirely excludes the use of old scrap in remelters.5

To summarize, in the first part of this thesis the overall purpose is to analyze the economics of primary aluminium production. Focus will be on geographical differences in efficiency, productivity and the degree of factor flexibility. In particular, potential differences between smelters located in mature - and to some extent - stagnant western economies compared to smelters located in regions where primary aluminium capacity has increased rapidly over the last one or two decades will be analyzed. In the second part, the relative importance of factors determining the supply and demand of secondary aluminium in Western Europe will be investigated.

CONTRIBUTIONS TO THE LITERATURE

The aluminium industry has, given its size and growing importance, seen surprisingly little attention from academic researchers, and with some exceptions regarding factor substitution (further discussed below) even fewer regarding the issues brought up in this thesis. Previous research includes; (a) global models of supply and demand (e.g., Charles River Associates, 1971); (b) efforts focusing on different aspects of the US aluminium market (e.g., Yang, 2005; Boyd et al., 1995; Rosenbaum, 1989, Froeb and Geweke, 1987; Reynolds, 1986; and Slade, 1979); (c) the different aspects on investment and location of smelter capacity (e.g., Skúlason and Hayter, 1998; Manne and Mathiesen, 1994; and Newcomb et al., 1989); and (d) traditional competitiveness comparisons (e.g., Adams and Duroc-Danner, 1987). While all

5 This situation might however change in the future, as recovery and recycling technologies improve. One example is that remelters have recently started to use small amounts of high quality old scrap. Thus the competition for scrap between refiners and remelters, already stiff for new scrap, might become more intense in the old scrap segment as well.
these efforts have clear qualities, the current thesis differs from these chiefly in its focus on relative efficiency and productivity measures as an aspect of competitiveness in the primary aluminium industry (among other things), and the focus on the recycling of aluminium in the secondary aluminium industry. However, there are still a number of studies relevant to the efforts made in this thesis, and these are briefly reviewed below. The review will follow the general areas under investigation in this thesis, i.e. efficiency and productivity, factor substitution and supply and demand for secondary (recycled) aluminium.

Efficiency and Productivity

Efficiency and productivity studies dealing with the aluminium industry are difficult to find. However, there are a number of studies of efficiency in other process industries of similar characteristics as the primary aluminium industry. The efficiency or lack thereof of the iron and steel industry has gained attention from researchers. Examples for the US steel industry includes Ray and Kim (1995) and Gruver and Yu (1985), and for the Chinese counterpart Ma et al. (2002), Zhang and Zhang (2001), Ray et al. (1998), Wu (1995, 1996) and Kalirajan and Yong (1993). Also the international pulp and paper industry has drawn some attention (e.g., Lee, 2005; and Yin 1999, 2000). All these studies apply either stochastical frontier analyses (SFA), a regression based method due to Aigner et al. (1977) or data envelopment analysis (DEA), a mathematical programming technique due Charnes et al. (1978) to analyze the relative efficiency of industries, firms or production units. There are four fundamental aspects of efficiency, namely technical-, allocative-, overall- (or economic-) and dynamic efficiency and how these measures compare for a given production unit or firm compared to its compatriots in a given industry (Cubbin and Tzanidakis, 1998). Technical efficiency can be further decomposed into what is sometimes referred to as ‘pure’ technical efficiency and scale efficiency (see, for example, Cooper et al., 2000). However, in order to estimate or calculate all the above efficiency aspects both engineering data and price data are needed. While all the above studies include some measure of technical efficiency, less than half also include some measure of the allocative efficiency and hence no measure of the overall efficiency, usually depending on the lack of input price data. Furthermore, only one of the above studies attempts to calculate a given value of scale efficiency.

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6 See paper 1 in this thesis for a more comprehensive discussion of the above papers.
7 The overall efficiency is the product of technical and allocative efficiencies.
8 This problem is most prominent in the studies dealing with the Chinese iron and steel industry, of which only Ray et al. (1998) calculates a measure of allocative efficiency.
In general these studies point to: (a) the majority of inefficiency in the steel and pulp and paper industries is allocative in nature; (b) considerable geographical variation in efficiency, with plants and firms in the west regularly faring better than plants and firms in developing economies; and finally (c) improvements in efficiency as time passes. Some of the studies attempt to explain efficiency variations with factors such as industrial agglomeration, vintage of the capital stock, ownership and level of resource control and investment structure, all variables which broadly may vary across locations.

As mentioned above there are a few studies dealing with productivity development in the primary aluminium industry, namely Bye and Førsund. (1990) and Førsund and Jansen (1983). While not explicitly using DEA-technique these studies still applies linear programming techniques to derive short run cost functions and deterministic production frontiers for the Norwegian aluminium industry. The main results indicate a rather slow technical change at the best practice plants, while there exist significant cost reductions due to the average smelters catching up with their best practice competitors.

The contributions of the papers in this thesis, apart from focusing on a largely neglected industry, are first that all the above efficiency measures will be explicitly calculated. Second, the entire global primary aluminium industry will be included; thus efficiency of a single smelter will be evaluated against the industry’s best performers, regardless of location. This is important since primary aluminium is a globally traded commodity and aluminium firms compete across the globe. Third, not only will regional differences in efficiency be measured but also efficiency across different smelter technologies will be explicitly accounted for. Fourth, in order to gain a deeper understanding of the causes of inefficiency in aluminium smelting, specific factor reductions will be calculated. Fifth, the impact of technological development and efficiency improvements over time will be accounted for and sixth and finally, a unique plant level data set provided by CRU Intl. (2004) covering nearly all primary aluminium smelters globally will be used.

**Factor Substitution**

A number of studies use statistical methods to estimate cost functions for primary aluminium smelting (e.g., Figuerola-Ferretti, 2005; Larsson, 2003; Gagné and Nappi, 2000; Tsekouras and Zagouras, 1998; and Lindquist, 1995). All these studies apply flexible cost function approaches; however only Figuerola-Ferretti, Larsson and Lindquist actually estimate own- and cross price elasticities for the input factors.
Larsson (2003) investigates economies of scope in the Norwegian primary aluminium industry. His main results indicate that the product mix influences factor demand and that Norwegian smelters are differentiating their output leading to less labour and more material and fuel intensive outputs. Lindquist (1995) studies the extent of *ex post* factor substitution with emphasis on the effect of increasing energy prices on factor use, in her case also for the Norwegian aluminium industry. Common for both studies are that they show that short-run factor substitution occur, even though the substitution elasticities are low.

The present dissertation is similar to the above two studies in applying a flexible cost function approach to test the hypothesis of zero *ex post* factor substitution. It differs however in that it also test whether short run factor substitution differs across smelter locations. Specifically, the investigation is focused on whether smelters located in mature market economies in Western Europe under pressure from increasing costs are more flexible than smelters in locations experiencing substantial greenfield investments, namely the Africa and Middle East region.

### Supply and Demand of Secondary Aluminium

Research focusing on the behaviour of metal recycling markets is rare, but does exist. If we limit ourselves to studies of the secondary aluminium market, there are even fewer. As the structure of the recycling process is similar across non-ferrous metals,\(^9\) studies dealing with other metals than aluminium, notably copper are also worth commenting on.

Three general lines of research have been identified. *First*, there are steady state models focusing on analyzing how the share of scrap metal in total metal supply is affected by for instance the growth rate of the economy (e.g., Radetzki and Svensson, 1979; Radetzki and van Duyne, 1985). However, these studies do not undertake any full-fledged empirical evaluation of the relative importance of the identified factors leading from one steady state to another. *Second*, there exist a number of econometric studies mainly focusing on explaining the supply and demand of metals in the global economy. Examples of such attempts are the copper market studies by Fisher et al. (1972), Wagenhals (1984) and Suan Tan (1987)\(^{10}\) and the aluminium markets have been studied by, for example, Charles River Associates (1971) and Slade (1979).\(^{11}\) Many of these studies, however, focus on the primary metal market and

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\(^9\) For example, the process that generates the scrap stock is likely to be similar across non-ferrous metals.

\(^{10}\) Suan Tan’s study is one example of the many World Bank commodity market studies.

\(^{11}\) Slade studies both the copper and aluminium market and the interaction between them. Slade’s study is also confined to the US copper and aluminium market.
treat the secondary metal sector only briefly. Thus, their contribution to analysis of the secondary sector is somewhat marginal.¹²

The third line of research is a number of studies dealing (more or less) explicitly with the functioning of secondary metal markets. Most of these studies have dealt with recycled copper in the US (e.g., Bonczar and Tilton, 1975; Slade, 1980a, 1980b; and Stollery, 1983 (which also includes ferrous scrap)). Examples of aluminium recycling studies include Grace (1978) and Carlsen (1980), where the former is the only study reviewed here that includes other nations (namely six OECD countries) than the US. While the studies differ in methodological approach, the general conclusions from these research undertakings can be summarized in the following points; (a) the supply of secondary metal is inelastic, where the new scrap fraction is mainly determined by overall metal consumption; (b) the cost of using recycled metal is influenced by the availability of scrap metal which is a function of the stock of scrap and its development; (c) secondary metal markets represent a competitive fringe to the primary market; (d) primary, secondary and scrap metal prices are tightly correlated; and (e) the importance of final good demand and structure in explaining secondary metal supply.

The main contribution of the two papers in section two of this thesis is, contrary to the above studies, the focus on metal recycling in Western Europe, which in terms of applied research almost is ‘virgin’ territory. In two different papers, different models of supply, demand and pricing for recycled aluminium in Europe will be empirically tested something which, at least to the author’s knowledge, never has been done before. The data covers the four main secondary aluminium producing nations in Western Europe, namely Germany, France, Italy and the United Kingdoms over the years 1983-97. The present studies also differ methodologically from the above efforts in the sense that, in the fourth paper, explicit account is taken for the influence of the most important end use sector, the automobile industry, contrary to using some aggregate measure of economic activity such as GDP. In addition, the fourth paper is one of few studies that explicitly estimates short run behavior in a secondary metal market. The fifth paper in this thesis follows Slade’s (1980a) modeling of the US secondary copper market (i.e., the formulation of the price formation process and the application of a Cobb-Douglas cost function to derive a model of secondary aluminum supply). However, in the calculation of the stock of scrap, here actual consumption shares of each end use sector are used instead of assuming a fixed value. Finally, the above studies in most cases use data covering the 1950s up until the mid 1970s. Thus, yet another contribution

¹² Slade (1979) gives a full treatment of the secondary copper and aluminium sectors. However, since her methodological approach is similar to her 1980a and 1980b work, it will not be reviewed further here.
of this thesis will be to update research on the behavior of secondary metal markets to present time.

**SUMMARY OF PAPERS**

This dissertation consists of five papers of which the first three concerns the global primary aluminium industry, while the last two focus on the secondary primary industry in Western Europe. Papers I and II investigate static efficiency and productivity development over time, attempting to illuminate possible differences across different smelter locations and different smelter technology types. Paper III focuses on estimating factor substitution elasticities for the primary aluminium industry, and investigates whether there are differences in these across smelter locations. Papers IV and V, finally, analyze the supply and demand of secondary aluminium. Special attention is paid to the importance of the end use structure of aluminium and the impact of scrap availability.

I. Calculating and Decomposing the Sources of Inefficiency within the Global Primary Aluminium Smelting Industry – A Data Envelopment Approach (with Bo Jonsson)

The purpose of this paper is to evaluate the efficiency of the global primary aluminium industry. Efficiency is here taken to be evaluated relative to some benchmark, i.e., the smelter or smelters identified as the most efficient in the data set, thus forming the production frontier. The performance of individual smelters, specifically their technical, allocative and scale efficiencies will be calculated by the means of Data Envelopment Analysis (DEA) using a cross section smelter level data set for the year 2003. In order to assess and contrast the performance of smelters at different locations, facing dissimilar policy and factor supply environments, smelters will be divided into geographical regions. Furthermore, the technology used will also be evaluated in terms of the above efficiency measures. For each technology and region, measures of potential technical and cost wise factor savings will be calculated in order to assess specifically in what way production factors improvements can be made and approximately how large these improvements are.

The findings indicate that in general smelters are highly efficient given the scale of operation. However, many smelters operate with increasing returns to scale and thus we find significant scale inefficiencies. Thus, many smelters operate off the industry’s minimum efficient scale and would lower average cost if the scale of production was increased. The findings also indicate that there are substantial allocative inefficiencies in the industry, i.e.,
smelters are inefficient in changing the factor set up according to market prices. Overall, there are significant variations in the level of efficiency across smelter locations and the main technology used. The allocative efficiency is particularly low in regions such as China and the CIS-region. Finally, we find the most substantial factor reductions occurring in regions with low technical and allocative efficiencies.

II. Regional Differences in Productivity Growth in the Primary Aluminium Industry
(with Bo Jonsson)

The purpose of this paper is to evaluate the development and regional differences of total factor productivity (TFP) in the global primary aluminium industry using data envelopment analysis techniques and Malmquist indices. The evaluation is based on smelter level data covering the period 1993-2003. We anticipate ex ante that differences in factor costs and competitive pressure will cause differences in TFP across smelter locations. In particular the expectation is that TFP changes will be higher in high cost regions where capacity is either stagnant or even declining. In such regions, the TFP development is likely to focus on efficiency improvements while in regions where capacity is expanding, most of TFP change will come from technical change. In order to further illuminate productivity developments across regions we also calculate TFP-changes by technology type. This is motivated since the two main technologies used, the Soderberg- and Prebake processes tend to be concentrated to different parts of the world.

The result of the analysis indicates that there are variations in TFP changes across regions. With the exception of smelters in Western Europe, there has been considerable TFP improvements in North America and the Oceania region, both high cost regions with few recent capacity increases. However, much of the TFP change stems from improvements in technology. Chinese smelters along with smelters in the CIS-region have experienced relatively weak improvements in TFP, allegedly due to rapid capacity expansions. In regions showing strong capacity growth, most of the TFP change comes from technical change, as expected. Furthermore, the results also show that efficiency change exhibits a slightly more variable development over time than do the technical change component of TFP. Finally, we do not find support for the notion that the dispersion of different smelter technologies has affected regional smelter performance.
III. Factor Demand Flexibility in the Primary Aluminium Industry: Evidence from Stagnating and Expanding Regions (with Patrik Söderholm)

The purpose of the paper is to estimate the degree of ex post factor demand flexibility in the primary aluminium industry in Western Europe and the Africa-Middle East (AME) region. In Western Europe smelter capacity additions have been stagnant and there are risks for smelters to be phased out. In the AME-region, capacity has increased substantially and there are plans for further expansions. We investigate the hypothesis that as smelters in Western Europe are under severe pressure, they should have become more flexible in their factor uses so as to alleviate some of the competitive demands. Furthermore, we also analyze whether the oil crises in the 1970s implies that smelters built after the energy cost increase have been more flexible in terms of short-run factor use.

We use a Translog variable cost function model, which is estimated employing a panel data set at the individual smelter level over the time period 1990-2003. The empirical results suggest that the null hypothesis of zero ex post factor substitutability can be rejected. Overall aluminium smelters in the AME region show evidence of higher short-run own- and cross-price elasticities than their competitors in Western Europe, at least when it comes to labour and electricity demand. Western European smelters can however more easily switch between the material input and electricity. The results also suggest that in both regions the demand for electricity has over time become less sensitive to short-run price changes, while the substitution possibilities between labour and material have increased but only in the AME-region. The liberalization of the western European electricity markets in combination with the rigid labour markets in this part of the world suggest that the shift in production capacity from the western world to the AME-region as well as China may continue.

IV. Short-Run Demand and Supply Elasticities in the West European Market for Secondary Aluminium (with Stefan Hellmer)

Secondary aluminium accounts for almost a quarter of total aluminium consumption in Western Europe. In some countries, such as Italy, the secondary industry has by the end of the 1990s become far bigger than the primary aluminium industry. The purpose of this paper is not to estimate recycling ratios per se, but to explore the supply–demand relationships in the market for secondary aluminium alloys in Western Europe. This effort is not only interesting because it adds to our understanding of an important recycling market. It will also help us understand the high volatility in secondary aluminium prices. Volatility in own prices might have detrimental effect on the willingness to undertake long-term investment in the industry, with possible negative ramifications for recycling. The main agent in this market is the
secondary refiner producing casting alloys for a wide variety of applications with the auto industry representing the most important end user. In countries with a domestic auto industry between 60-85 percent of secondary production is consumed by this industry. The secondary refiner is the bulk consumer of old aluminum scrap from worn-out, retired products; therefore the refinery industry traditionally has been the nucleus of the aluminium recycling industry even though its position has increasingly been challenged by remelters over the last decade.

Based on a standard short-run microeconomic model, the determinants of supply and demand are identified. Using pooled time series and cross sectional data for Germany, France, Italy and the UK for the time period 1983-97, the model is estimated by the Two Stage Least Square method to avoid the problem of simultaneity. Furthermore, as we have data in panel format, we generalize the classical regression model by using a fixed effects approach.

Our results show that the short-run supply of secondary aluminium is own-price inelastic. A one percent own price increase would only increase supply by 0.17 percent. Given the short-run framework the low input elasticities are not surprising, Output will fall by a mere tenth of a percent due to a one percent increase in scrap prices, which is surprisingly little considering that scrap accounts for nearly 70 percent of variable input cost. We tentatively conclude that the low elasticity of scrap prices in the short run depends on delivery commitments vis-à-vis customers. On the demand side the single most important factor identified is the level of auto production. A one percent increase in the derived demand from auto manufacturers would (in the short-run) lead to half a percent increase in secondary aluminium demand, demonstrating the importance of this industry for the secondary aluminium industry. We further demonstrate that the cyclical nature of automobile demand in combination with the inelastic supply of secondary refineries will have a great impact on secondary aluminium price, and thus partly explains the observed volatility in secondary aluminium prices.

We conclude that the empirical results indicate both inelastic demand and supply, something, which is reasonable considering the adopted short-run framework. This indicates that policies aimed at increasing aluminium recycling by manipulating price can be ineffective considering the low own price elasticity of secondary supply. Policies aimed at decreasing the cost of recycling, for example, by making scrap cheaper will also run the risk of not getting the job done, as the low supply response to changes in scrap prices indicates. We speculate that policies not directly aimed at recycling might turn out to do better. For example, increased public and private demands for better fuel efficiency and safety in cars might potentially increase the demand for materials with a favourable strength to weight ratio,
such as aluminium. Considering the already strong position of secondary aluminium within the transport sector of the economy, deeper penetration and increased demand for secondary aluminium is a possibility.

V. Economic Models of Secondary Aluminium Pricing and Supply

The first purpose of the paper is to examine pricing in the market for secondary aluminium, especially the interdependencies with the market for primary aluminium. We develop a simple model assuming that the price for secondary aluminium is determined by the price of primary aluminium as well as industrial activity. The entire secondary industry is thus viewed as a price taker. Using pooled time series and cross section data for Germany, France, Italy and the UK over the time period 1983-97, the OLS results show an inelastic, though still sizeable reaction of the secondary price to changes in primary price, leading us to conclude that the secondary aluminium industry as a whole indeed seems to be a price taker. The inelastic response also leads us to further conclude that the secondary industry cannot completely fill the slack caused by fluctuating primary prices. The cause of this is that substitution between secondary and primary only takes place in the market for castings.

A second purpose is to refine the supply elasticity estimates from paper IV, and further to calculate and estimate the impact from the stock of aluminium scrap on the supply of secondary aluminium. To do that, a theoretical model of secondary aluminium supply is developed; it integrates microeconomic theories of production and cost with a simple model of scrap generation and accumulation. The parameters of the supply model are estimated in ‘two steps’, using data for the same countries and time period as above. In the first step, we explicitly include input costs for scrap. The TSLS results show an inelastic, though still quite significant own-price response of secondary supply. However, we demonstrate that since the input price of scrap is not independent of the output price of secondary aluminum alloys, the resulting own price elasticity will be overestimated.

Thus, in a second step, an alternative supply function accounting for this is estimated, where we assume that secondary and scrap prices have a fixed relationship to each other. The results of this exercise indicate, as expected, a significantly reduced own-price elasticity. A one percent increase in price leads to a fifth of a percent increase in secondary output, which is in accordance with previous research. We show that due to the inelasticity of supply, subsidies to secondary refiners equaling almost 20 percent price increase will increase the market share of recycled aluminium with only one percent. Thus, we confirm the result from the first paper that price driven policies will fail to achieve substantial increases in recycling.
We further calculate a continuously growing stock of scrap during the period in question. The increased availability of aluminium scrap increases the probability of secondary producers to find the wanted quality, thus lowering the cost of recycling. The impact on supply is however found to be small, less than one tenth of a percent. Given that increased recycling probably must come from the stock, the low responsiveness of supply from increase scrap availability indicates that attempts to stimulate ‘mining’ of the scrap stock will be costly.

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Calculating and Decomposing the Sources of Inefficiency within the Global Primary Aluminium Smelting Industry:
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ABSTRACT
The purpose of this paper is to evaluate the efficiency of the global primary aluminium industry. Efficiency is here taken to be evaluated relative to some benchmark, i.e., the smelter or smelters identified as the most efficient in the data set, thus forming the production frontier. The performance of individual smelters, specifically their technical, allocative and scale efficiencies are calculated by the means of Data Envelopment Analysis (DEA), using a cross section smelter level data set for the year 2003. In order to assess and contrast the performance of smelters at different locations, facing dissimilar policy and factor supply environments, smelters are grouped into geographical regions. Furthermore, the technology used will also be evaluated in terms of the above efficiency measures. For each technology and region, measures of potential technical and cost-wise factor savings will be calculated in order to assess specifically in what way production factors improvements can be made and approximately how large these improvements are. The findings indicate that; (a) smelters are overall highly efficient given the scale of operation; (b) many smelters operate with increasing returns to scale and thus we find significant scale inefficiencies; (c) substantial allocative inefficiencies exist within the industry and; (d) there are significant variations in the level of efficiency across regions and technology used. The allocative efficiency is particularly low in regions such as China and the CIS-region. Finally, the greatest potential for factor reductions is in labour input in China, the CIS-region and in Asia.

Keywords: aluminium, primary aluminium smelting technology, technical efficiency, allocative efficiency, scale efficiency, data envelopment analysis.

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INTRODUCTION

The primary aluminium industry in many ways shares the general positive development in the mineral and metal industries seen over the last decade. Capacity and output have expanded rapidly and are now approaching an annual level of 30 Mt. However, the aluminium industry has been grappling with three interrelated forces with profound effects on the structure of the industry and the efficiency and competitive standing of individual smelters, namely; the geographical relocation of smelter capacity, the ongoing technological shift in smelter technology and the increasing scale of the operations of smelters.

Much of the capacity expansion over the last 10-20 years has come in nations and regions offering cheap energy, either by having access to abundant energy sources or by subsidizing energy aimed at large scale consumers, or regions with forecasts of strong demand growth. Some of these regions are - at least to some extent - characterized by having little previous technical experience in process industries, lack of experience in market economics, manifested by insufficient institutional set-ups, partly dysfunctional factor markets, managerial lack of control over resources and general managerial inexperience. In addition, in some nations and regions, investment in aluminium smelters may be driven by other motives than purely profit, including industrial and regional development and diversification.

The investments in capacity expansion along with rising energy- and environmental costs in primarily Western Europe and parts of North America have also affected the technological progress in the industry. First, the industry has for a substantial time employed two main varieties of smelter technologies; the Soderberg continuous- and the Prebake method. Due to better energy and environmental performance, the Prebake technology is largely replacing the Soderberg technology in most greenfield- and brownfield investments undertaken. This trend is however not uniform across regions; Chinese smelters, while rapidly expanding maintain substantial capacity with Soderberg technology, as do a large number of smelters in the CIS-countries. Second, technological progress in aluminium smelting seems also to have had an impact on the minimum efficient scale of the industry; the size of average smelter rapidly increases as new plants are being established and existing ones expanded (King, 2001). While the scale of operations generally has increased over time, the size distribution of capacity also seems to have become more geographically dispersed. Relatively small scale smelters of high age are found in, for example, Western Europe but also in China where there are a number of start-up small scale smelters (using the Soderberg technology).
Resource processing industries such as aluminum smelters are often considered to be technically efficient - i.e., on or close to the production frontier - due to the nature of their technology. Processing technologies are usually well established with seemingly little differences between plants and locations. The economics of plant operations and the technical requirements of the production process itself usually predict that process industry units are operating close to capacity limits. However, due to the discussed reasons, we argue that there are reasonable causes to believe that many of today’s aluminium smelters are less than fully efficient, either applying their technology insufficiently or in an inefficient scale compared to their best competitors. Moreover, we argue that there could exist significant differences across nations and regions in both purely technical efficiency and the ability to allocate production factors efficiently.

Hence, the overall purpose of this paper is to evaluate the efficiency of the global primary aluminium industry. In doing so we will analyze to what extent any identified inefficiencies are caused by smelters being inefficient in their use of technology or lacking in their ability to allocate resources efficiently. Efficiency is here taken to be evaluated relative to some benchmark, i.e., the smelter or smelters identified as the most efficient in the data set, thus forming the production frontier. The performance of individual smelters, specifically their technical, allocative and scale efficiencies will be calculated by the means of Data Envelopment Analysis (DEA), a non-parametric programming methodology first proposed by Charnes et al. (1978), using a cross-section smelter level data set for the year 2003.

In order to assess and contrast the performance of smelters at different locations, facing dissimilar policy and factor supply environments, smelters will also be grouped into geographical regions. Furthermore, the technology used will also be evaluated in terms of the above efficiency measures, specifically the efficiency differences between the two main methods used, the Soderberg continuous technique and the Prebake technology. Thus, we will be able to answer by how much short-run variable cost could have been reduced both per technological type and per region if best practice would have been applied. An additional contribution of our study, important not the least from an industry- and management perspective, is that for each technology and region, measures of potential technical and cost wise factor savings will be calculated in order to assess specifically in what way production factor improvements can be made and approximately how large these improvements are.
There exist few economic studies of the aluminium industry whatsoever and none explicitly dealing with the industry’s efficiency of operations (at least to our knowledge).\(^1\) However, in Table 1 we list a number of studies dealing with efficiency issues in the iron and steel industry (e.g., Ma et al., 2002; Zhang and Zhang, 2001; Ray et al., 1998; Wu, 1995, 1996; Ray and Kim, 1995; Kalirajan and Cao, 1993; and Gruver and Yu, 1985) and the pulp and paper industry (e.g. Lee, 2005; Yin, 1999 and 2000).

**Table 1. Previous Efficiency Studies Applied on Process Industries**

<table>
<thead>
<tr>
<th>Study</th>
<th>Industry</th>
<th>Data Description</th>
<th>Method</th>
<th>Efficiency measures</th>
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<tbody>
<tr>
<td>Lee (2005)</td>
<td>Forest &amp; paper</td>
<td>2001 accounting data for 97 forest companies globally</td>
<td>DEA</td>
<td>TE: 0.843 (VRS)</td>
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<td>SE: 0.899</td>
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<tr>
<td>Yin (2000)</td>
<td>Pulp</td>
<td>1996 data covering factor use &amp; prices at 102 mills globally</td>
<td>DEA &amp; SFA (C/D &amp; TL) (compares methods)</td>
<td>TE: 0.9715 (DEA-VRS)</td>
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<td>AE: 0.882 (DEA-VRS)</td>
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<td>OE: 0.856 (DEA-VRS)</td>
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<td>OE: 0.921-0.951 (SFA)</td>
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<tr>
<td>Yin (1999)</td>
<td>Pulp</td>
<td>1994 data for 70 mills across 10 countries around the Pacific Rim</td>
<td>DEA</td>
<td>TE: 0.950-0.994 (VRS)</td>
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<td>AE: 0.859-0.945 (VRS)</td>
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<td>OE: 0.834-0.929 (VRS)</td>
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<td>SE: Qualitative</td>
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<tr>
<td>Ray, Seiford &amp; Zhu (1998)</td>
<td>Iron &amp; steel</td>
<td>1989 data for 34 Chinese firms</td>
<td>DEA (AR) (both CRS &amp; VRS calculated for input based and output based models)</td>
<td>TE: 0.77</td>
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<td>AE: 0.79-0.79</td>
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<td>SE: Mostly IRS</td>
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<td>Wu (1995)</td>
<td>Iron &amp; steel</td>
<td>1984-92 data for 61 Chinese firms</td>
<td>SFA (C/D)</td>
<td>TE: 0.75 (average over period)</td>
</tr>
<tr>
<td>Ray &amp; Kim (1995)</td>
<td>Steel</td>
<td>1958-1986 aggregated industry data for the US</td>
<td>DEA</td>
<td>TE: 0.86-1.00 (VRS)</td>
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<td>(dep. on year)</td>
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<td>AE: 0.81-1.00 (VRS)</td>
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<td>OE: 0.72-1.00 (VRS)</td>
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<td>(dep. on year)</td>
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<tr>
<td>Gruver &amp; Yu (1985)</td>
<td>Steel</td>
<td>1951-1980 aggregated industry data for the US</td>
<td>Linear programming (not DEA specifically)</td>
<td>TE: 0.93-1.00</td>
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<td>AE: 0.73-1.00</td>
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<td>OE: 0.73-1.00</td>
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\(^1\) The studies that do exist focus on other topics related to the aluminium production technology and use other methods. For example, some studies use econometric techniques to estimate (among other things) factor substitution elasticities (e.g., Lindquist, 1995; Tsekouras and Zagouras, 1998; Larsson, 2003 and Blomberg and Söderholm, 2007), technological vintage effects (e.g., Gagné and Nappi, 2000) and pricing- and investment behaviour in the primary aluminium industry (e.g, Figuerola-Ferreti, 2005). Another strand of research is represented by Førsund and Jansen (1983) and Bye and Førsund (1990) who derive short-run production functions in a putty-clay framework for the Norwegian primary aluminium industry using linear-programming like techniques.
Similar to the primary aluminium smelting industry, both these industries utilize capital intensive, energy demanding processes and compete on a global market. We therefore provide a short overview of these studies.

The studies in Table 1 vary in purpose, scope and method. Some apply stochastic frontier analysis (SFA) developed by Aigner et al. (1977), while others use data envelopment analysis (DEA) due to Charnes et al. (1978). The former is a regression based method while the latter is a non-stochastic, non-parametric linear programming technique. With one exception, all studies discussed here apply one or both of these methods.

Whereas some of the studies utilize cross-section data and thus aim at comparing efficiency across the industry in one nation or across a larger sample, other studies focus more on studying how efficiency have developed over time, i.e., they apply panel data. Most of the studies with the latter focus find increasing efficiency as time passes. All studies present at least partial estimates of technical efficiency; less than half of the studies present any measures of allocative efficiency. This limitation can of course be a conscious choice, but it is likely to be caused by the difficulty to gather price and cost data, a problem magnified in non-market economies.

The studies on the Chinese iron and steel industry exemplify this problem since all but two lack such estimates. In the studies that do include allocative measures it can be seen that, regardless of industry or geographical scope of the study, allocative inefficiency is a major contributor to overall inefficiency. Thus, even in the cases where technical efficiency is rather high, as in the paper and pulp industry and the US steel industry, neglecting allocative efficiency seriously overstates the overall efficiency (which cannot be estimated without allocative measures).

As for the scale efficiency measure, only three out of seven of the studies using DEA as a tool, decomposed technical efficiency measure into its constituent parts. Thus, these studies miss out on the fact that the plant or mill might operate far off from what is the industry’s most productive scale. Again, this may imply overstating the overall efficiency. For the DEA-studies calculating scale efficiencies, only one (Lee, 2005) actually gives a score. Lee shows that in the forest and paper industry firms could improve efficiency by more ten percent if they were at the most productive scale. For the SFA-type studies, several include plant or firm size as an explanatory variable in the regression. The outcome gives contrary to the DEA approach no explicit measure of scale efficiency but instead enables comparison of technical efficiency across firms belonging to different size classes. The result whether there are any returns to scale are somewhat mixed and probably interlinked with ownership (since
most large Chinese steel works are controlled by the central state). However, the available evidence points towards the conclusion that many Chinese steel works can do better if they become bigger. Aside from the effect from scale, several of the SFA studies also attempt to measure how efficiency is affected by factors such as industry agglomeration, the vintage of the plant and the type of ownership and level of control of resources and investment structure.

Concerning the results in general it is clear that Chinese iron and steel works have significantly lower technical, allocative and overall efficiency scores than their counterparts in the US and compared to what is demonstrated for the pulp and paper industry. Ray et al. (1998) present allocative efficiency estimates as low as 39 percent for Chinese steel plants, i.e., efficiency could be improved by 61 percent at some steel plants simply by adjusting factor mixes according to prevailing prices. In the studies on the pulp and paper industry, which all have a wide geographical scope, scores for different regions are shown. One conclusion is that mills in the west exposed to market economics for a long time achieve higher estimates than mills in regions with emerging economies or more state-controlled economies. Even though no explicit attempt is made in the pulp and paper studies to explain the regional variations in efficiency, it might be speculated that the same forces are at work as might explain the low efficiency figures for the Chinese steel industry, i.e., lack of management control over all resources and partly dysfunctional input markets.

Our contributions, aside from focusing on the aluminium industry are as follows; first, we will calculate all four efficiency measures defined by Farrel (1957). Hence, we will be able to answer questions about the sources of technological inefficiency; is it inability to apply the technology properly and do smelters have returns to scale left to capture? Second, in order to highlight both the ongoing technological shift and the relocation of production in the aluminium industry, we will calculate all efficiency scores above for several different countries and regions and the two main technologies used in the aluminium industry. This will enable us to highlight if the technological shift has the potential to increase efficiency or if the old technology still is efficient. Moreover, some of the competitive advantages of building new smelter capacity in locations with abundant and cheap energy might be offset if these locations – often those in less developed market economies – display lower efficiency due to, for example, lack of allocative efficiency. Third, since factor use and thus potential technical and allocative inefficiencies vary across regions and technology, we will provide measures on specific factor reductions in order to achieve efficiency. This is important not only for smelter management in different types of smelters and regions of the world, but also for policy making, for example concerning energy policies aimed directly at or indirectly affecting
heavy process industries. To capture cost savings and competitive advantages if best practices are applied, we need to know what factors to focus on and how much they should be reduced (or increased) to become efficient.

The paper proceeds as follows: In the following section the main characteristics of the primary aluminium smelting process are presented along with some comments on cost differences due to the technology used and the location of smelters. We then outline the features of the DEA-method and the four efficiency measures are discussed. In the following two sections, we discuss the data used and present our calculated efficiency scores divided first by technology and then by geographic location of the smelters. Regional and technology specific measures of factor savings are also discussed in the latter section. The paper ends with some concluding remarks in the final section.

**ALUMINIUM PRODUCTION AND COSTS:**
**TECHNOLOGICAL AND LOCATION ISSUES**

The primary aluminium industry is made up of more than 230 smelters located in 46 countries and today production and consumption volumes of aluminum are second only to steel among metals (King, 2001). Primary aluminium is made in three separate steps. In the first step, bauxite ore is mined within a belt 20° north and south of the equator. In the second step, alumina (aluminium oxide) is extracted from the bauxite ore in an alumina plant using the Bayer process. The alumina is then shipped to a primary aluminium smelter for the third and final step in the process.

A standard smelter operation applies apart from alumina four other main inputs; electricity, labour and various anode and bath materials to produce primary aluminium. A smelter technically consists of one or several so-called pot lines, each consisting of a number of reduction cells or pots, connected in series to a source of direct electrical power. Each cell is filled with an electrolytic bath where the alumina is dissolved. A direct electrical current is then passed from a carbon anode which is lowered into the bath. The electrolysis that takes place when the electrical current passes through the bath breaks down the alumina into its constituents, oxygen and aluminium metal. The carbon anode is gradually used up during the process and need to recurrently be replaced. While the oxygen settles at the anode to form oxygen, the liquid aluminium sinks to the cell floor and is periodically tapped from the cell and taken to the cast house, where the aluminium metal may be alloyed with other metals in

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2 The five factor inputs discussed here make up approximately 80-90 percent of the variable costs accruing to the pot line. Other variable costs include site administrative costs and maintenance (especially pot relining) costs.
holding furnaces. Finally, the alloys (or pure aluminium) are poured into moulds to form billets, slabs, T-bars and ingots and sold as primary aluminium products.

There are two characteristics of the aluminium production process that need emphasising. First (as discussed above), the electrolytic process can broadly be separated into two categories; the Soderberg continuous self baking method and the Prebake method depending on how the carbon anodes are replaced. In the former, the carbon raw materials in the form of a paste mix is cyclically added to the cell and baked into a solid anode by the heat generated by the cell itself. In the latter, the anode is manufactured in a separate plant (the ‘anode centre’) using its own dedicated furnace. The anode is then introduced as a whole block in the reduction cell. Generally, the Soderberg method is considered to be less labour using while the Prebake method demands less electricity (King, 2001).

Second, the technology, regardless of variety is characterized by its putty clay nature (see, for example, Bye and Førsund, 1990). The choice of specific technology, i.e., Soderberg or Prebake, is thus of importance for aluminium smelters since the possibilities to change factor set ups in response to changing input prices in the short run are limited. For example Gagné and Nappi (2000) demonstrate that variable costs can potentially be reduced by more than 30 percent if a smelter changes from the most to the least costly technology.

Figure 1 depicts the variable cost curves for Soderberg- and Prebake technology smelters, and for smelters using a mix of the two technologies. It is noteworthy that the entire cost curve for both ‘pure’ Soderberg smelters and for smelters using a combination of Soderberg and Prebake technology is positioned above the cost curve for ‘pure’ Prebake smelters. The question arises whether the observed differences in costs are attributable purely

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3 The process is named the Hall-Heroult electrolytic process after its inventors. The general process has been unchanged over the last century although it has undergone major modifications and developments.

4 In the Soderberg method, the electrical current enters trough the anode trough rows of pins that are inserted into the carbon anode either horizontally or vertically, each making a specific type of the basic Soderberg technology. In this paper we however disregard this distinction.

5 Again, there are several types of Prebake methods, depending on how the alumina is introduced into the reduction cell. We continue to disregard these fine differences.

6 The prime example is the alumina requirement, determined by chemical laws to slightly less than two tons per ton of output. Electricity use, though more varying across smelters than alumina, is also considered difficult to change in the short-run (see for example Blomberg and Söderholm, 2007).

7 The least efficient (i.e., highest variable cost) technology in Gagné and Nappi’s study is the vertical stud Soderberg method, whereas the most efficient is the point feed prebake system. Gagné and Nappi’s study employs a translog cost model using cross-section smelter level data.

8 The cost curves in Figure 1 represent the costs of the five main inputs used, alumina, electricity, labour and anode and bath materials. Thus, it should be noted that the curves do not correspond to the full variable cost. All factors with prices measured in local currency has been re-calculated (by the CRU) into US$ using official exchange rates per 2003. Also, while the CRU database covers a significant share of the world population of smelters, some small scale smelters in China are not included in the sample.
to differences in technology or if some part is due to differences in the efficiency of operations, and thus if (at least) parts of the gap can be closed by improving smelter level operations. However, it is of course as likely that there are substantial inefficiencies also at Prebake smelters.

![Figure 1. Variable Cost of Production per Ton of Primary Aluminium](source: CRU (2004)).

Moreover, with investment in new technology and smelters during the last decade and a half, the scale of smelters has increased rapidly, possibly indicating changing minimum efficient scale of operations. The average capacity of smelters has for instance increased from 130 kt in 1990 to 207 kt in 2004 (CRU, 2004), and so has the dispersion around the average capacity, potentially signifying that many smelters are not operating at optimal scale. For instance, the standard deviation around average capacity increased from 85 kt in 1990 to 171 kt in 2004. The claim that the increased deviation indicates that more smelters are operating at a non-optimal scale hinges on the shape of the long run average cost curve (LRAC) and the economies of scale in the industry. If the industry is characterized by a large segment of constant returns to scale (i.e., a flat LRAC), capacity differences would not matter and costs would be virtually the same over the entire capacity range. We, however, hold it likely that any flat segment of the LRAC is short and the shape of the industry LRAC indeed is U-shaped. More dispersion, thus, indicates that more smelters operate further away from the efficient scale.

The capacity of smelters per technology is displayed in Table 2. As might be expected since most new or expanded smelters are using the Prebake technology, the average capacity of such smelters is substantially larger than the corresponding capacity figures for ‘pure’
Soderberg smelters. This indicates potentially more profound scale problems at the latter kind of smelters.\(^9\)

**Table 2. Smelter Capacity per Technology Type in 2003 (1000s tons)**

<table>
<thead>
<tr>
<th>Output Ktons</th>
<th>Prebake</th>
<th>Soderberg</th>
<th>Mixed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max</td>
<td>719</td>
<td>945</td>
<td>899</td>
</tr>
<tr>
<td>Min</td>
<td>24</td>
<td>16</td>
<td>73</td>
</tr>
<tr>
<td>Average</td>
<td>220</td>
<td>144</td>
<td>225</td>
</tr>
</tbody>
</table>


Displaying the variable cost across regions instead of smelter technology reveals considerable differences in costs (see Figure 2).\(^{10}\) Some traditional production centres such as North America have relatively low costs along the curve. Even Western Europe comes out fairly well. At the same time, some of the fastest expanding regions such as China seem to have significantly higher costs along most of the curve. These differences can be explained only partially by the prevalence of technology in a particular region. As briefly mentioned, in China for example, small scale Soderberg smelters are still common. More prominently however is of course each region’s comparative advantage in the particular factors demanded to produce primary aluminium. The relative abundance of factors of production is of particular importance when it comes to electricity.\(^{11}\) For instance, the Africa and Middle East region offers abundant natural gas resources which make up for cheap electricity for aluminium smelters, Oceania have cheap coal produced electricity and parts of North America (mainly Canada) have cheap hydro power generated electricity. The variation in the existence of preferential long term contracts between utility and smelter and other means to change the cost of energy across regions further explain the variation in cost found in Figure 2. Finally, however, parts of the observed cost variations between regions may have to do with differences in efficiency. Such differences may be due to the level of technical expertise and management ability at the smelter level. In many expanding regions, such as China and the CIS-region, the experience of market economics is supposedly rather brief; thus the potential for cost improvements aside from what is mandated by factor endowments and policies should be substantial if practices at the smelter level could be enhanced.

\(^9\) It can however be noted that the smelters with the individually largest capacity are of the Soderberg and mixed technology-type.

\(^{10}\) The cost curves in Figure 2 again represent a selection of factor costs (see footnote 8)

\(^{11}\) According to Gagné and Nappi (2000), 60 percent of the variability in variable production cost across smelters emanate from differences in electricity costs
Finally, considering the geographical dispersion of capacity we can note that Western and Eastern Europe along with China and Asia have smelters with on average below world average capacity, while for example the Africa-Middle East- (AME) and the CIS-regions have smelters above the average scale of capacity (see Table 3). The frequency of investment to some extent explains this pattern. Whereas some regions such as the AME-region (partly due to favourable energy costs) have experienced plentiful investments in large scale smelters using the most modern equipment, greenfield investments in China have to some extent been made in relatively small scale smelters (often using Soderberg technology). In Western Europe almost no major greenfield investment or capacity expansion has been undertaken for the last two decades, leaving this region with an relatively old and small-scale stock of smelters. These substantial differences in the scale of smelter capacity between regions raise further considerations on the observed cost differences across regions.

Table 3. Smelter Capacity per Region in kt.

<table>
<thead>
<tr>
<th>Output Ktons</th>
<th>W.E1)</th>
<th>N.A2)</th>
<th>Oceania</th>
<th>L.A3)</th>
<th>CIS4)</th>
<th>E.E5)</th>
<th>China</th>
<th>AME6)</th>
<th>Asia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max</td>
<td>270</td>
<td>437</td>
<td>460</td>
<td>430</td>
<td>945</td>
<td>192</td>
<td>719</td>
<td>559</td>
<td>324</td>
</tr>
<tr>
<td>Min</td>
<td>42</td>
<td>50</td>
<td>165</td>
<td>51</td>
<td>24</td>
<td>35</td>
<td>16</td>
<td>55</td>
<td>35</td>
</tr>
<tr>
<td>Average</td>
<td>137</td>
<td>234</td>
<td>273</td>
<td>217</td>
<td>297</td>
<td>107</td>
<td>162</td>
<td>271</td>
<td>172</td>
</tr>
</tbody>
</table>


In Figure 2 and henceforth in this paper, the regions that are not self evident are as follows; CIS equals Azerbaijan, Russia, Tajikistan and Ukraine. Oceania equals Australia and New Zealand. Western Europe comprises smelters in both the central, southern, northern and the western parts of Europe. The Asian group includes all smelters on the Asian continent with the exception of China and the Middle East. The latter region has for convenience been grouped with smelters located on the African continent.
To summarize this section; there are clear divergences in costs – and thus competitiveness – between both smelter technologies and smelter locations. Part of these variations can be explained by the comparative advantages of the technologies and locations. We maintain, however, that significant fractions can simply be due to underperformance in one respect or another at a considerable number of smelters compared to the most efficient operations in the industry. In the next section we present models to measure and quantify these potential inefficiencies.

THEORETICAL FRAMEWORK AND DEA MODELS

The Production Function and its Dual

The production process of a production unit ($i$) is assumed to be represented by the following general production function:

$$y = f(x_i, z_i, A(t))$$  \[1\]

where $y_i$ is the level of production at time period $t$, $x_i$ is a vector of variable input quantities, $z_i$ represents a vector of quasi-fixed inputs and $A(t)$ represents both the “physical” state of technology and the general know-how at time period $t$. The production function in [1] is assumed to be twice continuously differentiable, increasing and concave in $x$. If $y_i$ is maximized given $x_i$, $z_i$ and $A(t)$ then technical efficiency in an absolute sense prevails. Thus, the maximum possible amount is produced at a certain time period given variable and quasi-fixed input quantities and technology.

In most cases the production function [1] and its functional form is unknown. However, relying on duality, the cost function which is assumed to represent the underlying production technology can be used and be represented by:

$$c[y, w, z, A(t)] = \min_{x \geq 0} \{w^T x : x \in V(y)\}$$  \[2\]

13 Sometimes it is argued that $A(t)$ should be interpreted broadly, not only as technological level, but also including general know-how (managerial, organizational etc).
where \( w_a \) is a vector of strictly positive prices for the variable inputs, \( w_a x_a \) is the inner product of input prices and quantities and \( V(y) \) is the input requirement set, i.e., all input combinations capable of producing output \( y \). In line with, for example, Chambers (1994), to ascertain the existence of the cost function we assume that the input requirement set \( V(y) \) is both non-empty and closed. Equation [2] is increasing in \( y \) and \( w \) as well as homogenous of degree one and concave in \( w \), and represents the minimum cost of producing a given level of output over a given time period at given input prices. The cost minimization problem is restricted by the state of technology and the level of quasi-fixed inputs. Thus, given the objective of cost minimization, the cost function defines absolute overall efficiency in the short-run for the production unit. Contrary to the production function in equation (1), where input quantities are assumed to be exogenous to the producer, the cost function approach in [2] instead assumes exogeneity of input prices, thus presuming atomistic competition for inputs. Regardless of which approach that is chosen (i.e., equation [1] or [2]), firms are presumed to respond optimally to changes in their environment given their behavioural aims.

The DEA-Approach to Efficiency Measurement

The significance of measuring and understanding the factors behind efficiency or lack of it has been the subject of extensive research ever since Farrell’s (1957) seminal work in which efficiency was measured as the deviation of the observed output from an idealized production frontier. Several methods have since been developed to measure the actual degree of efficiency within an industry or sector of the economy. The two most frequently used methods are stochastic frontier analysis (SFA) which is a regression based method developed by Aigner et al. (1977), and data envelopment analysis (DEA) due to Charnes et al. (1978). There is no clear-cut view in the literature about preferred method to analyze efficiency, since both have their pros and cons.14

DEA is a non-stochastic, non-parametric linear programming technique for evaluating the performance of Decision Making Units (DMU). DMUs are usually defined as entities responsible for turning input(s) into output(s), such as firms and production units. A DMU must, as the name indicates, have at least some degree of freedom in setting behavioural goals and choosing how to achieve them. DEA makes use of observations on, for example, input-output relations from a given population of DMUs, and then optimizes on each individual

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observation with the objective to calculate a discrete piece-wise frontier determined by the set of Pareto efficient DMUs.\textsuperscript{15} Thus, the performance of each individual DMU is measured as the distance from its most efficient peer on the efficient frontier, with the restriction that all DMUs in the sample are on or below the frontier (e.g., Charnes et al., 1994; Thanassoulis, 2001). Contrary to estimation by stochastic methods, when using DEA no assumption must be made about the functional form relating independent variables to the dependent variable, such as those in the general cost minimization equation \[2\].\textsuperscript{16} Another advantage is that since the frontier in DEA is formed by the best practice DMUs, it sets a clear benchmarking target for the inefficient DMUs to achieve. In the present study we adopt the DEA method to measure efficiency.

The intuitive idea behind the DEA approach is summarized in Figure 3 below. The solid line represents the efficient frontier derived from a sample of DMUs (labeled D and E), each utilizing different amounts of inputs $x_1$ and $x_2$ to produce various amounts of the output $Q$ (here normalized to 1). The frontier itself represents best practice given the sample data – i.e., DMUs on the frontier might still be inefficient in an absolute meaning as proposed by equation \[2\]. By using DEA a range of efficiency measures can be derived for DMUs that deviate from the frontier. Because efficiency calculations in DEA are based on actual observations, all resulting efficiency scores are relative, referring to one or more other DMUs on the frontier. For example, in Figure 3 DMUs D and E are on the frontier, thus they are technically efficient, i.e., given the sample they use the minimum observed amount of factors to produce one unit of output.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{dea.png}
\caption{The DEA-Approach to Efficiency Evaluation}
\end{figure}

\textsuperscript{15} Pareto efficiency could, using an input oriented approach be defined as follows. A DMU is Pareto-efficient if it is not possible to decrease the use of any of the DMUs inputs without increasing at least another of its inputs and/or without decreasing the level of at least one of its outputs (Thanassoulis, 2001).

\textsuperscript{16} However, this proposition has been challenged by for example Forsund and Hjalmarsson (2004).
A DMU such as C uses more of input $x_1$ and less of $x_2$ compared to DMU E and the reversed is the case when compared with DMU D, both judged technically efficient. We can then infer that DMU C is inefficient in one input factor compared to the two efficient DMUs. A radial contraction of DMU C’s input use along a ray from origo would increase the efficiency up until point $\beta$, which is on the efficient frontier. We could then measure the level of technical efficiency of unit C as the ratio $0\beta/0C$.

The dotted line $(w_1x_1+w_2x_2)$, passing through C, represents the cost at prevailing factor prices of making one unit of output using C’s combination of inputs. However it is clear that C can lower the cost of production by a radial decrease of inputs and thereby move to a point such as D. At the intersection between the Cost min line and the ray from origo the point $\alpha$ represents a ‘virtual’ DMU. Using this virtual DMU $\alpha$, we define allocative or cost efficiency by the ratio $0\alpha/0\beta$. The distance between the two points, $\alpha$ and $\beta$, shows how far the technically efficient input mix $\beta$, falls short of allocative efficiency mix $\alpha$. Finally, the ratio $0\alpha/0C$ demonstrates how far from overall or total efficiency unit C is.

**Technical Efficiency Measures**

To measure the technical efficiency of a specific aluminum smelter, we initially employ the basic DEA model due to Charnes et al. (1978), known as the CCR model. In the CCR-model it is assumed that constant return to scale (CRS) prevails, i.e., a radial contraction or expansion of all observed DMUs are assumed possible. Here we utilize the input oriented approach where output is exogenously determined by for example competitive forces17, and the DMU hence should minimize its factor use to at least achieve the given output level.

Assume a sample of competitive DMUs under CRS producing a single output $y$ (e.g., primary aluminium production) using a vector of factors $x$, then the input oriented CCR-model calculates the efficiency score ($\theta$) (here abbreviated $TE_{CRS}$ for technical efficiency) of DMU$_p$ by solving the following linear programming problem:

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17 See for example Figuerola-Ferreti (2005) and Boyd et al. (1995) for arguments lending support to notion that the market for primary aluminium is competitive in nature.
\[
\begin{align*}
\min & \quad \theta = \lambda \mathbf{x}_s \\
\text{subject to} & \quad \theta \mathbf{x}_s - \lambda \chi \geq \mathbf{0} \quad [4] \\
& \quad \gamma \chi \geq y_0 \quad [5] \\
& \quad \lambda \geq 0 \quad [6]
\end{align*}
\]

where the scalar \( \theta \) \([0<\theta \leq 1]\) is the radial or proportional reduction in all inputs in order to make the DMU efficient. The vector \( \chi \) represents the amount that each input and output should be multiplied with to create the “virtual” efficient DMU, \( \beta \). Constraints [4] and [5] denote input excesses and output shortfalls, respectively. A DMU with a score \( \theta=1 \) is thus termed (globally) technically efficient and on the frontier. All DMUs with scores \( \theta<1 \) are using more factors then its best practice competitors to produce a given amount of output. If, for example, the score for a particular DMU is \( \theta=0.8 \), then that DMU must reduce its inputs by 20 percent in order to move to the frontier.

The assumption of CRS might not hold, though. For instance in many capital intensive industries such as primary aluminium production, returns to scale are likely to be increasing. Fortunately, the CCR-model can however, be augmented to capture variable returns to scale (VRS) by adding the constraint:

\[
\mathbf{e} \lambda = 1 \quad [7]
\]

where \( \mathbf{e} \) is a row vector with all elements equal to one. Together with the condition \( \lambda \geq 0 \) this condition imposes convexity conditions on allowable ways in which the DMUs in the sample may be combined so the feasible region will be a subset of the CCR model. The constraint basically limits the sum of the adjustment variable \( \lambda \) to equal one.

This model is due to Banker et al. (1984) (usually dubbed the BCC-model). By imposing constraint [7] the convex hull will embrace all returns to scale possibilities, i.e., variable returns to scale is permitted (see Cooper et al., 2000, for further discussion and for a proof of the constraints). The BCC-hull embraces the data more tightly then the hull constructed by the CCR-model, as it captures only the technical inefficiencies given the scale of a particular DMU. Usually the BCC-score therefore is called pure technical efficiency (TE\(_{VRS}\)) as to separate it from the TE\(_{CRS}\)-score (Ibid.).

- 15 -
We can further trace the sources of TE-inefficiency by decomposing it into the above demonstrated TE_{IRS} and scale efficiency (SE) components. Following Färe et al. (1985), the scale efficiency score can be defined by the ratio: \[ SE = \frac{\hat{\theta}_{CCR}}{\hat{\theta}_{BCC}} \] where \( \hat{\theta}_{CCR} \) and \( \hat{\theta}_{BCC} \) are the efficiency scores obtained by solving the CCR- and the BCC-models respectively. An SE-score less than one indicate that the DMU at hand is not operating at a point consistent with CRS or long run equilibrium and therefore either should increase or decrease its scale of operations to achieve efficiency. Following Färe (1985) we modify constraint [7] so that:

\[ \varepsilon \leq 1 \]  

This condition is equal to demanding non-increasing returns to scale (NIRS), something which allows us to qualitatively classify whether any scale inefficiencies come from increasing (IRS) or decreasing returns to scale (DRS), respectively (see Lee (2005) for an application). 19

**Allocative Efficiency Measures**

The preceding section focused on the technical-physical aspects of efficiency. Given information on input and output prices allocative efficiency can also be measured. DMUs might be efficient in an engineering sense, but still not allocate inputs optimally according to the prices of inputs the DMU meets. DMUs are in the following model assumed to minimize cost of production. Evaluating the degree of attainment of this goal is measured to show how far the technically efficient input mix falls short of minimizing the cost of production:

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18 For a discussion of the problems with the scale efficiency concept as defined in the DEA-literature, see for example Forsund and Hjalmarsson (2004).

19 Returns to scale are reported running the DEA Solver Pro software. When variable returns to scale was assumed and the BCC-model duly applied using condition [9], 143 smelters out of 151 were found to operate under increasing returns to scale when we solved the LP-problem in equation [3]. Furthermore, eight smelters exhibited constant returns to scale and non-decreasing returns.
\[
\begin{align*}
\min & \quad \mathbf{c}_o \mathbf{x}_o \\
\text{subject to} & \quad \mathbf{x}_o - \lambda \mathbf{y} \geq \mathbf{0} \quad \text{[10]} \\
& \quad \mathbf{y} \mathbf{\lambda} \geq \mathbf{y}_o \quad \text{[11]} \\
& \quad L \leq \lambda \leq U \quad \text{[12]} \\
& \quad \mathbf{\lambda} \geq \mathbf{0} \quad \text{[13]}
\end{align*}
\]

where \( \mathbf{c}_o \) is a vector of unit input costs for DMU \( o \) which may vary from one DMU to another. Given the optimal solution \((x^*, \lambda^*)\) of the above problem, the cost or allocation efficiency (AE\(_{VRS}\)) is defined by:

\[ AE = \frac{\mathbf{c}_o \mathbf{x}^*}{\mathbf{c}_o \mathbf{x}_o} \quad \text{[15]} \]

where allocation efficiency is thus measured as the maximum ratio between actual observed costs at DMU \( o \) to the calculated optimal cost. In the linear programming model above, \( L=U=1 \) corresponds to VRS (the PTE-measure) using the BCC-model. Thus the AE\(_{VRS}\)-score obtained should be interpreted as the possible deviation from the best practice, given the scale of the particular DMU in question. The difference between the TE\(_{VRS}\)-efficiency calculation above and the AE\(_{VRS}\)-calculation in [15] can be referred to as ‘suboptimal employment’, which can be both positive, i.e., the DMU uses too little of an input or negative, i.e. the DMU uses too much of a certain input. Suboptimal employment is caused by allocative inefficiency and can mathematically be expressed as:

\[ S_o = \frac{\mathbf{x}_o - \mathbf{x}^*}{\mathbf{x}_o} \quad \text{[16]} \]

where the ratio \( S_o \) represents a vector of factor reductions or increases at DMU \( o \), which should be undertaken by that particular DMU to realize allocative efficiency. It should be noted that some authors, for example Bye and Førsund (1990), claim that primary aluminium smelting exhibit putty-clay characteristics. If this is true, short-run substitution of input factors is nearly impossible, as factor set ups are defined at the point of construction. A smelter deemed allocatively inefficient thus have limited options to counter this problem and any
measure of allocative efficiency indicating suboptimal unemployment may be perceived as ‘meaningless’. However, as other authors show (e.g., Lindquist, 1995; Larsson, 2003; Blomberg and Söderholm, 2007), there is, albeit limited still room for short-run input factor substitution in the primary aluminium production process. Thus, we maintain that it is important to quantify possible allocative inefficiencies.

**Overall Efficiency**

In Figure 3 above, the $\text{TE}_{VRS}$ -measures refer to the ratio $0B/0C$, and the $\text{AE}_{VRS}$ -measure in [15] refers to the distance $0A/0B$. However, as previously discussed, a DMU operating at A would still not be efficient in an overall meaning. We need a measure of overall or total efficiency ($\text{OE}_{VRS}$), i.e. how far off the originally observed values at C fall short of minimizing cost. In Figure 3, this refers to the ratio of $0A/0C$. Given that we have calculated the $\text{TE}_{VRS}$ and the $\text{AE}_{VRS}$ scores, the $\text{OE}_{VRS}$ -measure is simply the product of the $\text{TE}_{VRS}$ and $\text{AE}_{VRS}$, such as:

$$\text{OE}_{VRS} = \text{TE}_{VRS} \times \text{AE}_{VRS}$$

[17]

In this paper we present estimates of the $\text{TE}_{CRS}$ - $\text{TE}_{VRS}$ - $\text{SE}_{VRS}$ - $\text{AE}_{VRS}$ - and $\text{OE}_{VRS}$ - efficiency measures for different smelter technologies and regions. Necessary factor changes ($S$) to establish efficiency for each technology and region will be analyzed.

**DATA AND PROGRAMMING ISSUES**

The data on inputs and costs used to measure smelter efficiency are derived from the Aluminium Smelter Cost Database, a proprietary database provided by CRU International Ltd. CRU collects the data from several sources such as questionnaires, interviews, plant visits, published information, industry contacts and CRUs own estimates (see CRU, 2004 for further information). Using consultancy data to make broad international comparisons might give rise to questions about the quality of the data and certainly demands caution. However, since our purpose is to evaluate efficiency at the individual smelter level for a large number of geographical region worldwide, few other options remains. Furthermore, CRUs large client base within the metal industries and its long experience in undertaking the collection and
systemization of plant level data causes us to judge the data reliable. The data from CRU cover 151 primary aluminium smelters operational in 2003.  

In Table 4, we list the inputs and costs used in the efficiency calculations together with some basic statistics. The inputs we include are alumina, labour, anode related inputs, bath materials and electricity. Taken together, they make up approximately 85 percent of the variable smelter site operating cost.

<table>
<thead>
<tr>
<th>Table 4. Statistics of Input, Output and Cost for 2003</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>INPUT CONSUMPTION</strong></td>
</tr>
<tr>
<td>Statistics</td>
</tr>
<tr>
<td>Max</td>
</tr>
<tr>
<td>Min</td>
</tr>
<tr>
<td>Average</td>
</tr>
<tr>
<td>SD*</td>
</tr>
<tr>
<td><strong>OUTPUT</strong></td>
</tr>
<tr>
<td>Smelter Output (Ktons)</td>
</tr>
</tbody>
</table>

| **INPUT COSTS**                                     |
| Statistics                                          |
| Max                                                 |
| Min                                                 |
| Average                                             |
| SD*                                                 |
| **OUTPUT**                                          |
| DC Electricity (US$/t)                              |

* SD=Standard deviation  

All input, output and cost measures refer to activities belonging to the smelter process itself i.e., the pot line. Therefore inputs and costs used in the bake furnace and cast house facilities are excluded. This omission is made to permit comparison across smelters. For example, some Prebake smelters do not have their own anode production capacity but instead buy the anodes from other smelters, making comparisons more complicated if we would include also the bake furnace stage of production in our analysis. Moreover, maintenance and pot relining costs were also excluded in the study.

One advantage of the DEA-method is that the values of the efficiency scores in equation [3], [7] and [10] are independent of the values of which the inputs are measured in

20 To maintain the confidentiality of the CRU proprietary data, smelters will never be named, and all efficiency scores and other results pertain only to groups of smelters, i.e., by geographical regions or technology.

21 However, even though CRU claims that this number represents the entire population of smelters, there might be small scale smelters (most likely in China) not accounted for. For example, for the year 1999, King (2001) lists 233 smelters worldwide so even though the CRU data used here are for another year (2003) there is a possibility that it is not a complete coverage.
(Cooper et al., 2003). Hence, there is no need to re-calculate the values of inputs on the same basis of measurement. The measures of anode and bath material use and costs presented in Table 4 represent the aggregated sums of several different input and cost components that together makes up the anode and bath material categories. All physical inputs are measured in per ton of primary aluminium produced, with the exception of labour which is measured as the number of pot line (process) employees. Electricity consumption is measured as the use in kWh per ton of finished aluminium in the electrolytic process itself, thus excluding any auxiliary electricity use in the plant. In some studies (e.g., Gagné and Nappi, 2000; Bye and Førsund, 1990) alumina is treated as a shadow factor to output motivated by the low variability in use. Alumina use is indeed governed chiefly by chemical laws, but according to our figures in Table 4, alumina use still varies between 1.92 to 1.96 tons per ton of output. Alumina has a cost share of approximately 40 percent, which makes us believe that it is still motivated to include it in our calculations. Finally, smelter output is measured in thousands of tons of primary aluminium.

All costs used in our study are measured in real 2003 US$ per ton of finished aluminium. The cost for alumina is based on the world price in US$ including freight costs to the smelter. The cost of anode and bath materials is the weighted average of the cost of the respective input groups components (see footnote 22), and also represents world prices in US$. These prices are further weighted by CRU Intl with a smelter-specific adjustment factor. We interpret this factor as the actual rate paid by the specific smelter, being either a discount or a premium of the world price. Labour costs are measured in the local currency and then transformed into US$ using the appropriate exchange rate. Finally, the cost of electricity presented by CRU is a weighted average of an internal transfer price (self-generated electricity) and a contract price, where the weights represent the input shares of total electricity consumption at the smelter level. The contract price is either fixed or a tariff linked to the LME three month price of aluminium. The existence of long-term contracts and transfer- and metal price linked electricity prices raise the question what the true, or shadow,

---

22 The Carbon/Anode input category is a weighted average of purchased anodes, petroleum coke, pitch material and packing coke. The Bath material input category is a weighted average of aluminium fluoride and croylile.

23 The correlation coefficient for alumina and aluminium in our sample is indeed very high at 0.99. According to Pedraja-Chaparro (1999) any two variables with, at the extreme a correlation of 1, offer no extra information to the DEA analysis and is hence redundant. We tested by excluding alumina as an input, whereby the overall BCC-efficiency score was lowered to approximately 0.91 from 0.99 when included. With only minor revisions the smelters forming the efficient frontier remained the same.

24 According to King (2001), slightly more than a quarter of the electricity consumed in primary aluminium production comes from captive power stations. Furthermore, in 2003 CRU estimates show that approximately 21 percent of world aluminium output was produced with metal price linked electric power contracts.
price of electricity is. However, since our data involve more than 35 countries facing very different electricity markets, shadow prices for each smelter are difficult and time consuming to obtain.

The linear programming problem presented in equations [3], [7] and [10] is first solved using the entire data sample, i.e., a common efficiency frontier is calculated for all smelters jointly regardless of technology used and geographical locations. Thus, we get efficiency scores for all individual smelters. In order to compare efficiency across technologies, smelters using a particular technology (Soderberg, Prebake or mixed) are grouped together and an average score for the particular technology is calculated based on the individual efficiency scores of the smelters in that group. We apply the same procedure to calculate regional efficiency scores.

Since DEA relies on “extreme” observations to form the efficiency frontier, outliers (atypical data) have the potential of severely affecting the calculated efficiency scores for some or all DMUs (e.g., Melão, 2005). Sexton et al. (1986) argue that reporting or other errors are most troublesome if they belong to DMUs forming the efficient frontier. Since it seems to us that there exist no single agreed upon method among DEA practitioners on how to diagnose the results, we here employ a version of the method suggested by Wilson and Jadlow (1982). In their work observations on the frontier are deleted until efficiency scores stabilize (see also Yin, 2000 for an application of this method). We performed a number of such tests where the problems in equations [3], [7] and [10] were solved over and again by; (a) deleting first the single most influential smelter, then the two most influential smelters;25 (b) deleting two large efficient smelters which did not serve as reference to any other smelter in the sample (thus we expected their exclusion not to affect scores significantly); (c) deleting two Chinese smelters that were defined as efficient when we did (b); and finally (d) deleting three smelters judged “atypical” because of their insignificant production and because they were shut down in the year preceding our evaluation. Even though smelters not part of the frontier should have limited, if any, impacts on the overall efficiency scores (Sexton et al., 1986), we also tested deleting all smelters with less than 50 kt production, which totaled 20 smelters in the current sample. Five of these smelters were on the efficiency frontier, but only one served as reference of some weight. All changes in efficiency scores, which smelters forming the frontier and the number of times a particular efficient smelter served as reference

25 An influential DMU is here defined as a DMU which affects a relatively large share of the other DMUs’ efficiency scores, i.e., smelters acting as references to many other smelters in the sample (Wilson, 1995).
for others in the calculations caused by this series of deletions were judged acceptable and thus we consider our result as reasonably stable.

While the programming solutions are still based on all 151 smelters, we have omitted the three smelters judged by us as “atypical” in (d) above, plus another small smelter also shut down in 2004 in the presentation of the results in the following section. The factor and cost savings suggested by the solution of the programming problems were “extreme” and likely caused by their smallness. Also, since they were shut down shortly afterwards their inclusion is of limited interest.

**EMPIRICAL RESULTS**

We start this section by discussing the various efficiency measures outlined above when the sample of smelters is divided according to the main technical variety of the electrolytic process used; the Soderberg and the Prebake process. We also include those smelters using a mix of both these methods. In the second part of this section, we repeat the analysis, now divided according to the geographical location of the smelter. In order to enhance the understanding and policy value for managers etc., we also analyze for what specific inputs that efficiency can be improved, and by approximately how much consistent with maintaining output.

*Efficiency and Smelter Technology*

Under the assumption of VRS the technical efficiency scores are close to unity for all three types of smelters (see column 4 in Table 5). The global average across all technologies stands at over 99 percent efficiency, thus indicating that in general, inputs can be reduced by less than one percent without affecting output. The least technically efficient smelter in the sample is still almost 98 percent efficient compared to its benchmark competitor (reference). The high $TE_{VRS}$-scores for aluminium smelters are likely to depend on the characteristics of the production process. Aluminium smelting is a capital intensive industry, where the production of a smelter usually does not deviate from capacity for more than brief periods. Other efficiency studies of capital intensive industries such as steel and paper and pulp manufacturing have found if not as high so at least similar technical efficiency scores if VRS is assumed (e.g., Yin, 1999, 2000; Lee, 2005).  

26 There are a number of efficiency studies employing either DEA or SFA, focusing solely on the Chinese steel industry (e.g., Ma et al., 2002, Zhang and Zhang, 2001; Wu, 1995, 1996) that report considerably lower technical efficiency estimates. These results might depend on both industry- and country specific causes. Still, given the growing importance of China in the aluminium industry and the similarity between the two industries, these results lend some weight to our suspicion that our TE-scores might be too high, especially when we in a later section discuss the results on a regional basis.
Table 5. Average Efficiency Scores per Technology in 2003

<table>
<thead>
<tr>
<th>Smelter Technology</th>
<th>TE$_{CRS}$</th>
<th>TE$_{VRS}$</th>
<th>SE</th>
<th>AE$_{VRS}$</th>
<th>OE$_{VRS}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Score</td>
<td>No. efficient DMUs</td>
<td>Freq. in ref. set</td>
<td>Score</td>
<td>No. efficient DMUs</td>
</tr>
<tr>
<td>Soderberg</td>
<td>0.252</td>
<td>1/43</td>
<td>62</td>
<td>0.988</td>
<td>1/43</td>
</tr>
<tr>
<td>Prebake</td>
<td>0.475</td>
<td>5/88</td>
<td>224</td>
<td>0.994</td>
<td>17/88</td>
</tr>
<tr>
<td>Mixed (S &amp; Pb)</td>
<td>0.392</td>
<td>1/16</td>
<td>3</td>
<td>0.994</td>
<td>2/16</td>
</tr>
<tr>
<td>Global average</td>
<td>0.401</td>
<td>7/147</td>
<td>204</td>
<td>0.992</td>
<td>20/147</td>
</tr>
</tbody>
</table>

TE$_{CRS}$: Technical efficiency (CCR) under CRS. TE$_{VRS}$: Technical efficiency (BCC) under VRS. SE: Scale efficiency. AE$_{VRS}$: Allocative efficiency under VRS. OE: Overall efficiency.

It can be noted that even if the difference in efficiency between Soderberg- and Prebake-type smelters are negligible under the VRS-assumption, the latter still seem to have an advantage since most smelters forming the efficiency frontier are of the Prebake variety and also (almost exclusively) serves as references for the inefficient smelters inside the front (see columns 6 and 7 in Table 5).

However, even if smelters tend to be efficient given their current size, it is clear that many smelters operate far off the industry’s most efficient scale. Solving the programming problem in equation [3] and [8] under the VRS-assumption, only seven out of the 147 smelters was reported operating at CRS and no one at decreasing returns to scale, i.e., a majority of smelters would improve their technical performance if their scale increased. Furthermore, studying columns 2 and 8 in Table 5, the technical efficiency scores under constant returns to scale assumption and the scale efficiency respectively show; (a) that the use of inputs on average could be reduced by close to 60 percent given production if all smelters would be producing at the industry’s most efficient scale; and (b) there exists a significant disadvantage for smelters of the Soderberg type compared to Prebake and mixed technology smelters.

We propose that the huge gap in scale efficiency is due to the rapidly increasing scale of smelters, both through greenfield projects but also through capacity addition at existing smelters. Start-up smelters and investments in expansions of existing smelters almost...
exclusively utilize Prebake technology. Aside from increasing the scale of smelters, the preference for Prebake technology when investing, has had the effect that Soderberg smelters now tend to be older than the equivalent Prebake smelter.\textsuperscript{28} A relatively new smelter could be assumed to be more productive and need less input than an equivalent older one, given such factors as the quality of management, technical expertise and so forth.

Before we comment on the results concerning the allocative (\(AE_{VRS}\)) and overall efficiency scores (columns 9 and 12 in Table 5) two caveats should be brought out. First, we only evaluate these efficiencies under VRS, i.e., given the current scale of the individual smelter. Second, since allocative (and thus partly also overall) efficiency is determined by the ability to respond to changing market conditions which are largely outside the control of smelter management, and furthermore should have little per se to do with the process technology used, the causes are possibly found in the experience of management and institutional differences. We conjecture that such differences broadly could be translated into meaning geographical location.

On average, almost all of the observed inefficiency in primary aluminium production is due to inputs not being properly allocated according to relative factor prices. Again Soderberg smelters come out as less efficient, with potential cost savings if they would use the same factor setup as their benchmark competitor(s) of around 15.5 percent on average compared to around 11 percent for Prebake and mixed technology smelters. An indication of the geographical dimension is that out of the 10 least allocative efficient smelters, half were found in the CIS region. Since a vast majority of smelters in the CIS region are of the Soderberg type, this helps explain the relatively poor cost performance of this technology type. The same reasoning applies to China as well which can be seen in Figure 2, where the cost curve for China is positioned above most of its competitors.

\textit{Factor Changes across Smelter Technologies to Achieve Technical Efficiency}

Even if aluminium smelters by and large are technically efficient at their given scale of operation (i.e., the VRS-assumption), there still is room for improvements. In this sub-section we explore by how much the different inputs should be reduced for the inefficient smelters to be as efficient as its benchmark competitor(s) and still maintain production. Figures 4a-e

\textsuperscript{28} We calculated the median age of Soderberg smelters in our sample (those with an identified start up year) to be approximately 47 years, while the median age of Prebake smelters is 34 years. Considering the rapid pace of start ups in especially China (where information about start up year is scant) these figures probably exaggerate the age of smelters in general.
show the projected minimum, median and maximum input reduction for each input and smelter to reach the efficient frontier. Furthermore, the boxes show the range of savings for 50 percent of the smelters of each technological category in the sample. The median input reductions are generally somewhere in the range of parts of a percentage up to 10 percent depending on input factor, however with great variability in the maximum possible reductions for the least efficient smelter(s). Since alumina usage is determined by chemical laws, the possible reductions and inefficiencies are as expected small. The median reduction ranges from a half to one percent over the different technologies (see Figure 4a). Small as these reductions may be, given that alumina represents roughly 40 percent of variable cost, the increased efficiency would still be important.

Figure 4a-e. Factor Changes per Technology for Technical Efficiency
The aluminium industry has since 1980 on average reduced its electricity usage by 10 percent (IAI, 2006). However, there exist still significant differences between smelters. Figure 4e shows that the median decrease in electricity usage to achieve full efficiency is approximately five percent for both Soderberg and Prebake smelters and around one percent for smelters using both technologies.

Considering labour the median smelters seem to be rather efficient, the median reduction for all three categories of smelters being close to zero or just a couple of percent. However, the potential reduction for 50 percent of the Soderberg and mixed smelters in the sample are huge. For the former category, half of the smelters can reduce employment at the pot lines with between one up to more than 25 percent. The considerable potential for labour reduction at Soderberg smelters is somewhat surprising, since the Soderberg continuous method should be less labour demanding than their Prebake counterpart (Gagné and Nappi, 2000) (see also section 2 for a technical discussion). The excess workforce at Soderberg smelters likely has to do with the fact that Soderberg smelters are more common in, for example, China and the CIS region, where wages are low and staffing levels are kept comparatively high. For both anode and bath materials, the median Prebake smelters are close to the efficient frontier, while their Soderberg competitors can reduce use by around 5 percent.

Before proceeding to discuss efficiency across regions, we sum up the above discussion in Table 6 below. Taking the input reductions for technical efficiency discussed above in conjunction with similar input reductions for allocative efficiency, we can calculate the variable cost for each technology-type that would prevail if smelters were fully efficient.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Observed AVC</th>
<th>Efficiency AVC</th>
<th>% Cost reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soderberg</td>
<td>1078</td>
<td>904</td>
<td>16.1</td>
</tr>
<tr>
<td>Prebake</td>
<td>1005</td>
<td>916</td>
<td>8.9</td>
</tr>
<tr>
<td>Mixed</td>
<td>988</td>
<td>931</td>
<td>5.8</td>
</tr>
</tbody>
</table>

29 To enable the calculation of AVC reported in Table 6, we also calculated the input reductions for allocative efficiency per technology in a similar way as for technical efficiency. However, since allocative efficiency as such is of more interest when discussing the location of smelters, we have chosen not to show the box-plots for these reductions here. The allocative input projections in conjunction with the ones displayed in Figure 4 are used to calculate the costs in Table 6 and are available upon request from the authors.
Since Soderberg smelters come out as the least efficient technology, smelters of this technical denomination could achieve the greatest cost savings if they move to the efficient frontier. The savings in variable costs would on average amount to more than 16 percent, almost twice as much as Prebake smelters. Such an efficiency improvement would result in Soderberg smelters becoming the low cost technology. It should be emphasized that due to the technological characteristics of primary aluminium smelting the necessary input reductions to achieve these cost savings might be hard to attain, especially in the short-run.

Regional Differences in Efficiency

As noted above some of the inefficiencies found have more to do with the location of a smelter and what follows from that than purely with the technology applied. Hence, we will here repeat the analysis from above focusing on regional differences in efficiency, important not least from a competition standpoint. Starting again with the analysis of efficiency given the current scale of smelters, Table 7 (column 5) shows that out of the 20 smelters defined as technically efficient smelters, 15 are located in the Western Europe, North America or Oceania. The average smelter in these regions is close to completely efficient. For example, smelters in Oceania are only on average only a tenth of a percent away from the efficient frontier. With the exception of one smelter in Latin America, a majority of all smelters in the world use the western smelters as references. In regions such as Eastern Europe, Asia, and China, no fully technically efficient smelters are found, and the two efficient smelters in the CIS region serve as reference only once, indicating that they may be technically efficient but are “atypical” in their technology and practices. Finally, Chinese smelters can, according to Table 7, improve their technical performance by almost 1.5 percent.

Under the VRS-assumption, two smelters each in Oceania, the Africa/Middle East- and CIS-regions were operating under CRS, along with one in North America. All other efficient smelters would improve short-run productivity if their scale would increase. To some extent this outcome is mirrored in the scale efficiency scores reported in column 8 in Table 7. Smelters in North America as well as smelters in the Oceania region stand out as the least inefficient from a scale perspective. In the latter region, smelters would however still be able to decrease their short-run input usage by almost a third if they all produced at a level consistent with the industry’s most efficient scale. As already mentioned, many smelters in China are relatively small-scale, which is reflected by the potentially huge productivity gains in the neighbourhood of more than 75 percent if their scale would be optimal.
It is possible that our TE- and SE-scores for China are slightly overestimated. Our data base does not cover all active smelters and the greatest discrepancy belongs to China were our database coverage is only approximately a third of the smelters active in 1999 listed by King (2001). Many of these smelters are of very insignificant size with capacities less than 20 kt. These small smelters are likely to have inferior technology, know-how and management and our results might therefore overstate the efficiency scores somewhat (see Ma et al., 2002, for arguments along this line for the Chinese steel industry). This caveat might further be especially important when considering the efficiency of Soderberg type smelters since this method dominates in China. Of the ten least technically efficient smelters globally all are Chinese of which half are of the Soderberg type and the other half is of the Prebake type.

| Region              | \( \text{TE}_{\text{CRS}} \) | No. efficient DMUs | \( \text{Freq. in ref. set} \) | \( \text{TE}_{\text{VRS}} \) | No. efficient DMUs | \( \text{Freq. in ref. set} \) | SE | No. efficient DMUs | \( \text{Freq. in ref. set} \) | \( \text{AE}_{\text{VRS}} \) | No. efficient DMUs | \( \text{Freq. in ref. set} \) | \( \text{OE}_{\text{VRS}} \) | Score |
|---------------------|-------------------------------|-------------------|-----------------------------|-------------------------------|-------------------|-----------------------------|---------|-------------------|-----------------------------|-------------------|-------------------|-----------------------------|-------------------|-------------------|-------------------|
| Western Europe      | 0.439                         | 0/147             | 0                           | 0.997                         | 7/30              | 159                         | 0.440   | 0.912             | 1/30                        | 71                | 0.909             |
| Eastern Europe      | 0.231                         | 0/147             | 0                           | 0.988                         | 0/7               | 0                           | 0.234   | 0.880             | 0/7                         | 0                 | 0.869             |
| North America       | 0.561                         | 1/147             | 13                          | 0.993                         | 6/25              | 50                          | 0.565   | 0.878             | 2/25                        | 146               | 0.872             |
| Latin America       | 0.417                         | 0/147             | 0                           | 0.997                         | 1/11              | 124                         | 0.418   | 0.850             | 0/11                        | 0                 | 0.847             |
| Oceania             | 0.670                         | 2/147             | 79                          | 0.999                         | 2/8               | 39                          | 0.671   | 0.913             | 1/8                         | 2                 | 0.912             |
| Asia                | 0.293                         | 0/147             | 0                           | 0.991                         | 0/6               | 0                           | 0.296   | 0.870             | 0/6                         | 0                 | 0.862             |
| CIS                 | 0.361                         | 2/147             | 65                          | 0.989                         | 2/14              | 1                           | 0.365   | 0.816             | 2/14                        | 2                 | 0.807             |
| China               | 0.232                         | 0/147             | 0                           | 0.986                         | 0/35              | 0                           | 0.235   | 0.871             | 0/35                        | 0                 | 0.859             |
| Africa & Middle East| 0.477                         | 2/147             | 132                         | 0.994                         | 2/11              | 7                           | 0.480   | 0.862             | 1/11                        | 26                | 0.857             |
| Global average      | 0.401                         | 7/147             | 0.992                        | 20/147                        | 0.404             | 0.876                       | 7/147   | 0.868             |

\( \text{TE}_{\text{CRS}} \): Technical efficiency (CCR) under CRS. \( \text{TE}_{\text{VRS}} \): Technical Efficiency (BCC) under VRS. SE: Scale efficiency. \( \text{AE}_{\text{VRS}} \): Allocative efficiency under VRS. OE: Overall efficiency.

Column 10 in Table 7 shows that only seven out of 147 smelters were fully efficient in an allocative sense, with some variation across regions. On average Western Europe and the Oceania region are the most efficient with allocative efficiency scores around 91 percent.
Also smelters in North America are just above the global average in allocation efficiency, as are perhaps more surprisingly smelters in Eastern Europe. The latter might be due to the significant market-oriented reforms undertaken in this region over the last decade and a half, forcing firms to become more competitive and take greater consideration to market conditions. The least efficient smelters are found in the CIS-region, were improvements in the input mix would reduce costs by as much as 18 percent. More surprisingly, concerning its comparatively brief spell with market economics, is China’s relatively favorable outcome concerning allocative efficiency, which is close to the global average. CRU (2004), for instance, claims that VAT tariff rebates, fast growth and the focus on regional development and not profit by provincial governments have made some Chinese smelters content on ensuring continued survival instead on achieving competitiveness. Still, the relatively high allocative efficiency reported here might again have to do with the above mentioned incompleteness of the Chinese part of our smelter sample, with many small smelters missing. This is further corroborated by a comparison with the study by Ray et al. (1998) (see Table 1) of the Chinese iron and steel industry. They report allocative efficiency scores from a low of 39 percent to a high of 79 percent, which is considerably lower than our estimates. Even if it should be done with great caution, a further comparison with the few other studies of the steel and pulp and paper industry in Table 1 reveals similar levels of allocative efficiency scores. On a general level, our results indicate that smelters located in mature market economies seem to be better in allocating resources in accordance with relative prices.

Finally, if we study the last column of Table 7, we can see that the overall most efficient smelters - given the scale of operations - are located in Western Europe, Oceania and North America, i.e., basically the traditional producing regions. This outcome can be explained by the combination of high technical efficiency and relatively good allocation efficiency in these regions. While much capacity has either been shut down or is under consideration for closure in North America (especially in the US) and in Western Europe due to high costs, it still seems as if high efficiency might offset at least some of the competitive disadvantage these regions have compared to other regions such as China where capacity has been expanding. With the previously mentioned caveat about the limited possibilities for factor substitution we next turn to discussing regional differences in what factor specifically that should be reduced – or in some cases increased.
Factor Changes across Regions for Technical Efficiency

Considering in what inputs reductions can be made without affecting output; labour, bath materials and electricity inputs stands out in Figure 5. According to CRU (2004), China, Asia and CIS have the lowest employment costs of all regions and it is in these regions we find the biggest potential decrease to attain efficiency. Smelters in China and the CIS can potentially undertake reductions between 15 and 25 percent. The least labour efficient smelter in these regions can reduce staffing levels by up to 75 percent compared to its reference on the efficiency frontier, with no harm to production. It should be noted that even though changes in factor use may be possible in the short-run (see discussion above), the high reductions reported here should be interpreted with caution. The other regions seem to have fairly limited needs to reduce labour inputs.

Figure 5a-e. Factor Changes per Region for Technical Efficiency
Anode and bath material inputs, which are less governed by chemical laws than alumina usage and more by engineering practices, show less of a pattern across regions. Smelters in North America, Western Europe and Oceania all seem to have only limited potential savings. Especially for anode materials, the median smelter can save only five percent or below across all regions. For bath materials, potential factor reductions vary more due to engineering practices applied. Again, western smelters seem to be relatively efficient. Smelters in China and the CIS come out as relatively technically inefficient in their use of bath material with reduction possibilities of around 30 percent. Finally, studying the potential for factor reduction in electricity, the median potential reduction is just below or above five percent, with the exception of Western and Eastern Europe and China, a group where the median smelter seems to be fairly efficient in its electricity use.

For China the somewhat surprising technical efficiency in electricity (considering the relative inefficiency in almost all the other inputs) might be explained by the shortfalls in electricity supply in China that put pressure on Chinese smelters to conserve electricity (CRU, 2004). In addition, China has together with the central parts of Western Europe faced the highest average electricity tariffs (Ibid), which is likely to put pressure on smelters to apply the best possible engineering practices.

Factor Changes across Regions for Allocative Efficiency

Figures 6a-e display the potential allocative changes per input and region. Generally, labour stands out as the factor with the best prospects for reduction. Even in the relatively efficient smelters in North America, Western Europe and Oceania, labour should be decreased by around 20 to 25 percent for allocative efficiency to prevail. In China and CIS the potential reductions and cost savings are again substantial; half of the smelters should reduce their labour force by between 70 and almost 90 percent for allocative efficiency. Again, the high estimates should be interpreted with caution and seen more as giving general direction and levels and not precise on the dollar savings.

This cost inefficiency is underlined by the fact that while there are smelters in the other regions that actually use too little labour and hence should increase their use by in some cases up to 50 percent to attain the same factor setup as their reference smelter on the efficiency frontier; no such smelter seems to exist in China and CIS. The pattern continues studying anode and bath material usage. Western smelters are fairly efficient allocating anode and bath materials in response to relative price changes, while China and the CIS are far off the allocative efficient input mix, with possible reduction in bath material hovering above 50
percent. The other regions are somewhere in between these two clusters. Considering electricity, the median reduction is between eight and fifteen percent across all regions.

To summarize our discussion about regional differences in efficiency, smelters in Western Europe, North America and the Oceania region come out as fairly efficient. The smelters in these regions are technically all close to fully efficient given their current scale, but more importantly, they have above the global average allocative efficiency scores, which imply high overall efficiency. Smelters in the CIS-region are trailing in technical efficiency; and above all they are trailing in their ability to use the efficient input mix making them the
least efficient region in an overall sense. Given the caveat that the prospect for modifying input usage in an aluminium smelter is limited in the short-run and likely is dependent on capital investments, it is still instructive to take the input reductions suggested above in Figures 5 and 6 and translate them into an average regional “efficiency” variable cost. This exercise is summarized in Table 8 below.

Table 8. Average Regional Observed and Efficient Short-Run Variable Cost, US$ per Ton of Output*

<table>
<thead>
<tr>
<th>Region</th>
<th>Observed AVC</th>
<th>Efficiency AVC</th>
<th>% Cost reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Western Europe</td>
<td>1025</td>
<td>953</td>
<td>7.0</td>
</tr>
<tr>
<td>Eastern Europe</td>
<td>1088</td>
<td>951</td>
<td>12.6</td>
</tr>
<tr>
<td>North America</td>
<td>950</td>
<td>848</td>
<td>10.7</td>
</tr>
<tr>
<td>Latin America</td>
<td>859</td>
<td>757</td>
<td>11.9</td>
</tr>
<tr>
<td>Oceania</td>
<td>804</td>
<td>749</td>
<td>6.8</td>
</tr>
<tr>
<td>Asia</td>
<td>912</td>
<td>800</td>
<td>12.3</td>
</tr>
<tr>
<td>CIS</td>
<td>910</td>
<td>740</td>
<td>18.7</td>
</tr>
<tr>
<td>China</td>
<td>1264</td>
<td>1121</td>
<td>11.3</td>
</tr>
<tr>
<td>Africa &amp; Middle East</td>
<td>922</td>
<td>815</td>
<td>11.5</td>
</tr>
</tbody>
</table>

* It should be noted that the AVC listed in this Table should only be interpreted as the sum of the five inputs used here, thus the costs in the Table do not fully correspond to the full AVC at smelters in a given region.

As should be expected, the “old” producing regions in the Western hemisphere cannot match the potential cost savings of the less efficient regions such as Eastern Europe, Asia and foremost the CIS-region. The latter region is already very competitive, but would according to our estimates become the cost leader if CIS smelters could realize the same engineering and managerial practices as the smelters on the efficient frontier.

SUMMARY AND DISCUSSION

In the global primary aluminium industry the cost of production varies over different geographical locations and across different technologies used in the smelting process. If all smelters were fully efficient, the competitive advantage/disadvantage would solely be a question of applying the low-cost technology at the location with the lowest costs for key inputs. However, as we demonstrate in this paper, there exist significant inefficiencies in the primary aluminium industry. Hence, competitive disadvantages can at least to some extent be alleviated if a smelter would behave as its most efficient competitor. Thus, we analyze using a Data Envelopment Approach and smelter level data the relative efficiency of primary
aluminium smelters. The results are presented on an aggregated level, i.e., by technology and by region.

Our findings indicate that primary aluminium smelters, given the scale of operations are highly technically efficient with only minor variations across technology and location. We infer that this result is attributable to the characteristics of the production process with high capacity utilization. Furthermore, the two major technological varieties, the Soderberg and the Prebake technology have been around for decades and thus are generally well known.

However, our results show significant scale inefficiencies. A vast majority of smelters operate under IRS and could improve performance if their scale was upgraded. For instance, if the average smelter would operate at the industry’s most efficient scale, input usage could be decreased by close to 60 percent for technical efficiency. It is clear that Soderberg smelters are trailing their Prebake and mixed technology counterparts significantly in this respect, which we conjecture is a result of the bulk of investments going to the latter technologies. Apart from the CIS-region and China, Soderberg smelters are closing down or being converted. Location-wise the most scale efficient smelters are found in the traditional aluminium producing regions in the West and in the Africa-Middle East region. In the other regions the potential for improvements in efficiency through increased scale is significant. Regarding technological efficiency it seems clear that primary aluminium companies should focus on improving the scale of operations at individual smelters. However, a caveat is of course that our results do not say anything about the cost of achieving scale efficiency. The capital cost of expanding a smelter by installing new pot lines etc. might outweigh any savings from improved scale efficiency.

Another source of inefficiency in the aluminium industry is caused by the divergence in input allocation from market signals. Not surprisingly, smelters located in mature market economies in the west, with a slight exception of smelters in North America, outperforms smelters located in regions where the experience with market economy is relatively brief. This indicates that improving management skills regarding how to respond to changing relative input prices might be of considerable importance for smelters, especially in regions such as China and the CIS-region. Two qualifications go with this recommendation: First, the global scope of our study makes it hard to say something about institutional deficiencies in input markets, since these usually are specific to a country or region. Second, the possibility for smelters to change their input mix with relative price changes to achieve better allocative and overall efficiency is likely to be limited in the short-run. Major input changes mainly occur with greenfield investments or upgrading of an existing smelter. Thus, even though some
smelters would have a lot to gain in lower cost in competitiveness by altering their input mix, their ability to do so without major technological changes is probably limited.

Since smelters in traditional aluminium-producing regions fair well in overall efficiency due to both high technical and allocative efficiency, the projected input changes to reach the efficiency frontier are relatively small and thus the accompanying cost savings are (while still significant) far less than in the less productive aluminium producing regions. In, for example, the CIS-region variable costs could be decreased by more than 18 percent if smelters in this region behaved as their efficient reference smelter. Soderberg-type smelters can gain more than 16 percent in costs and become the cost-leading technology, given that they apply the same practices as their reference smelters on the frontier. However, given the lack of investment aimed at this type of smelter (with the exception of the CIS-region and in China) we find it unlikely that this will happen.

Finally, although the proposed cost savings here to some extent hinge on factors that are difficult to change in the short-run and the caveat that the specific efficiency scores should be interpreted with caution, we believe it is fair to conclude that our results indicate that there are efficiency gains to be made in the aluminium industry, both across technologies and regions even in the short-run.

REFERENCES


Regional Differences in Productivity Growth in the Primary Aluminium Industry

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Abstract: The purpose of this paper is to evaluate the development of the total factor productivity (TFP) in the global primary aluminium industry using data envelopment analysis techniques and Malmquist-indices. The hypothesis posed is that there exist significant variations in the total factor productivity (TFP) of the primary aluminium industry across different regions and over time, measured by year-by-year changes in productivity. In stagnant regions, with cost disadvantages, mainly in the west, stronger TFP-improvements, especially in the form of enhanced efficiency is expected. The evaluation is based on smelter level data covering the period 1993-2003. The result of the analysis indicates that there are variations in TFP change across regions. With the exception of smelters in Western Europe, there have been considerable TFP improvements in both North America and the Oceania region, all high cost regions, however mostly from technical change. In some regions with strong capacity expansion, such as China and the CIS, has experienced relatively weak overall improvements in TFP, especially in terms of efficiency change.

Keyword: aluminium, primary aluminium smelting technology, technical efficiency, total factor productivity, Data Envelopment Analysis, Malmquist-index,

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INTRODUCTION

Primary aluminium production has increased rapidly worldwide over the last three decades with average annual growth rates of more than three percent. However, as the global output has grown, some nations and regions have benefited while others have experienced stagnation or even decline. For instance, the primary aluminium industry in the European Union started phasing-out more than two decades ago, and there exist continued threats of further capacity closures in the region in the near future (Commission Staff Working Document, 2006; Fischer, 2006). Another example is that since 1990 US production has fallen by approximately a third (Metal Statistics, 2004). Over the same period, a number of regions have seen output grow rapidly. Examples include Africa, the Middle East and perhaps most spectacular, China, which has ten-folded its output over the last two decades (Ibid.).

The main alleged explanation to the apparent loss of competitiveness of smelters in parts of the western industrialized world and the changing geography of aluminium smelting is the level and variability of input costs across nations and regions (see, for example, Nappi, 1992). Most important for aluminium smelting is access to abundant and cheap energy.¹ In these respects, smelters in the CIS-region, Canada, Africa and the Middle East, the Oceania-region and Latin America enjoy considerable cost advantages over smelters in, for example, parts of Western Europe, the US and China (CRU, 2004).² For smelters located in countries or regions with higher energy costs or other major factors of production compared to smelters in locations with lower costs, one way to counter an increasing competitive pressure is to try to decrease production costs by enhancing factor productivity over time. This can be done by either introducing new, cost saving technologies or practices or by using existing technology more efficiently, i.e., to catch up with the best practice smelters in the industry.

Primary aluminium production technology exhibits, at least to a degree, putty clay properties (see, for example, Førsund and Jansen, 1983 and Bye and Førsund, 1990). Factor set-ups and major improvements of the production process are determined and introduced

1 Transforming alumina into primary aluminium is a very energy intensive process. The production of one ton of primary aluminium regularly requires 13-16 MWh of electricity. Other factors affecting the competitiveness of smelters in a certain location are the presence and quality of economic infrastructure and institutions, the legacy of past investments and various public policies aimed at the aluminium industry (Nappi, 1992). The most important policies are usually those designed to artificially decrease energy cost for smelters (Ibid).

2 Chinese smelters pay electric power tariffs that are on average 3.5 times higher than the corresponding tariffs facing smelters in the CIS, the region with the lowest power tariffs for the primary aluminium industry (CRU, 2004). Thus, China is in this respect an exception since the rapid growth of smelter capacity has been realized despite the fact that Chinese smelters face the highest power tariffs in the world.
mainly when smelters are built, and not thereafter. It is therefore reasonable to assume that as investments tend to fluctuate over time, so will the pace of technological change in primary aluminium smelting, i.e., we will observe periods of rapid technological change as improvements are introduced followed by periods with a slower pace of change. It is also likely that productivity gains vary across regions depending on where investments are made. Furthermore, periods of investment and rapid technological change are also likely to breed periods of increased inefficiency. As innovators improve productivity by introducing new technology, late adaptors will fall further away from the production front. Variations in factor productivity due to the development of efficiency in factor usage are also likely to vary across locations. For instance, in their study of the international primary aluminium industry, Blomberg and Jonsson (2007) demonstrate differences between smelters across different regions in the ability to employ current smelter technology. Some extent these differences allegedly depend on differences in management practices, institutional framework and so forth at different locations. The development of such factors is likely to be variable between nations and regions. However, the study by Blomberg and Jonsson is only based on cross sectional data and thus do not say something about such possible developments over time.

In this paper we intend to illuminate the hypothesis that there exist significant variations in the total factor productivity (TFP) of the primary aluminium industry across different regions and over time, measured by year-by-year changes in productivity. In connection to this general question we will also raise an auxiliary hypothesis that given the cost disadvantages and mounting competitive pressures faced by smelters in stagnant production locations in the western world, we expect to find a more rapid TFP-development than in some of the fast growing aluminium smelting regions. To remain competitive or at least diminish existing competitive disadvantages of being located in high cost regions, smelters in, for example, Western Europe and North America should have stronger incentives to implement cost saving technologies and perhaps more important due to the lack of major green- and brownfield investments in these regions, improving efficiency.

At the same time as the geographical center of gravity is shifting, the aluminium industry has also been going through a technological shift that needs to be illuminated. The majority of greenfield smelters being built during the last two decades have used so called

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1 Facto substitution is however not completely absent. For example, Lindquist (1995) and Larsson (2003) demonstrate that even in the short-run there exists some potential for changing the input set up. A more recent effort reaching similar conclusions is the work by Blomberg and Söderholm (2007) in their comparative study of factor substitution possibilities in primary aluminium smelting in Western Europe and the Africa-Middle East region.
Prebake technology due to its (at least in theory) superior energy efficiency and environmental performance compared to the Soderberg continuous method, the other main technology in the industry (see next section for more on aluminium production technology). Existing smelters have also converted to the Prebake technology, leaving a number of smelters with twin sets of technologies. The exception to this trend is China and the CIS-region where significant Soderberg capacity is maintained. In order to provide a fuller understanding of regional variations in productivity development, we will also compare TFP-changes across the different technologies.

There is only a limited amount of empirical literature covering the economics of primary aluminium production, and yet fewer explicitly dealing with productivity changes. Lindquist (1995) uses a Translog cost function approach in her study of factor substitution in the Norwegian primary aluminium industry. Lindquist measures technological change by a time trend. While not discussing overall productivity growth, the study concludes that savings in labour use have come with increased smelter capacity and not primarily through technological change. Also using a Translog cost function and applying cross-section data for all smelters operational in 1994, Gagné and Nappi (2000) derive potential cost savings when smelters change from one technological vintage to another. Specifically they find large savings when the change is from Soderberg type smelters to the most modern variety of Prebake technology. They also find evidence of substantial variations across different regions. Again, Gagné and Nappi focus only on shifts in technology and not on overall productivity development. Førsund and Jansen (1983) and Bye and Førsund (1990) use a deterministic frontier approach deriving successive short run production functions for the Norwegian aluminium industry for the time periods 1966-78 and 1966-84, respectively. Both studies focus on three aspects of technological change; factor bias, productivity change and changes in substitution properties. The main findings indicate that technical change has been labour saving while periodically electricity using. Most of the improvements in electricity use came from inefficient smelters catching-up with best practice performance. The latter of the two studies finds changes in best practice technology amounting to 0.2 percent annually, while productivity gains from the average firm catching-up with best practice of about 4 percent.

While the first two studies do not make any distinction between technical changes, i.e., the movement of the production front and any potential catching-up effects, the latter two do. Still, they are limited only to Norway and an earlier era. Furthermore, applying a time trend such as the one in the Lindquist study assumes a smooth, continuous technological change. There is however little reason to believe that technological change and productivity
improvements occur in such an orderly manner. The literature on technological diffusion rather proposes that technological change (and hence productivity growth) often occurs in spurts (e.g., Stier and Bengtson, 1992).

In this paper we take a slightly different stance compared to the papers above. We measure the change in TFP by calculating Malmqvist productivity indices for the aluminium industry using smelter level panel data for the period 1993-2003. While the Malmquist index approach is fairly standard it has the advantage of letting us account for both the shift in best practice or technological change, and changes in efficiency, i.e. whether a smelter has improved its performance vis-à-vis its fully efficient competitors (e.g., Färe, 1994). This distinction is important not the least from a policy perspective. Changes in productivity caused by changes in technology depend on R&D efforts and barriers to innovation and diffusion, while changes in efficiency depend on factors such as institutional barriers, managerial slack and absence of competition thus demanding different policy responses (e.g., Dykstra, 1997). The use of smelter level data allows us to report result at different levels of aggregation; hence we will show the development of productivity divided both per technology and per region. The Malmquist indices will be based on a non-parametric frontier approach, namely data envelopment analysis (DEA) due to Charnes et. al. (1978).

The paper proceeds as follows. In the next section a brief overview of technological change and productivity development in the primary aluminium industry will be outlined. The following section works through the methodological framework, displaying the Malmquist indices used to analyze TFP and the linear programming problem used to derive them. The data used will be discussed next, followed by the empirical results. The paper ends with some concluding remarks and implications.

PRODUCTION TECHNOLOGY AND PRODUCTIVITY DEVELOPMENTS IN PRIMARY ALUMINIUM SMELTING

Primary aluminium is produced in three separate steps; the third step being the focus of this paper. In the first step, bauxite ore is mined within a belt 20° north and south of the equator. In the second step, alumina (aluminium oxide) is extracted from the bauxite ore in an alumina plant using the so called Bayer process. The alumina is then shipped to a primary aluminium smelter for the third and final step in the process where the alumina is transformed into primary aluminium by the Hall-Héroult electrolytic process. A standard smelter operation applies, apart from alumina four other main inputs; electricity, labour and various anode and bath materials to produce primary aluminium. A smelter technically consists of one or several
so-called pot lines, each consisting of a number of reduction cells or pots, connected in series to a source of direct electrical power. Each cell is filled with an electrolytic bath where the alumina is dissolved. A direct electrical current is then passed from a carbon anode which is lowered into the bath. The electrolysis that takes place when the electrical current passes through the bath breaks down the alumina into its constituents, oxygen and aluminium metal. The carbon anode is gradually used up during the process and need to recurrently be replaced. While the oxygen settles at the anode to form oxygen, the liquid aluminium sinks to the cell floor and is periodically tapped from the cell and taken to the cast house, where the aluminium metal may be alloyed with other metals in holding furnaces. Finally, the alloys (or pure aluminium) are poured into moulds to form billets, slabs, T-bars and ingots and sold as primary aluminium products.

As mentioned above, there are two main varieties of the Hall-Héroult process; the Soderberg continuous self baking method and the Prebake method. The difference between the two relates to how the carbon anodes are replaced. In the Soderberg process, the carbon raw materials in the form of a paste mix is cyclically added to the cell and baked into a solid anode by the heat generated by the cell itself. In the Prebake method, the anode is manufactured in a separate plant (the ‘anode centre’) using its own dedicated furnace. The anode is then introduced as a whole block in the reduction cell.

While the Hall-Héroult electrolytic process has kept its general characteristics since the method was invented in 1886, substantial productivity improvements and technical advances has been realized and put into practice. The improvements have focused mainly on three areas; (a) improving electricity efficiency; (b) improving labour productivity and (c) reducing emissions from the smelting process. Table 1 below lists the average cost shares for four input factors over the period 1995-2003 for nine regions. Even though cost shares vary substantially between regions, alumina and electricity together stand out contributing somewhere in the range of 70 to 90 percent of total variable costs. Alumina costs alone usually constitute not far from half of total variable costs at a smelter. The variety in alumina cost between smelters stems from differences in transport charges and costs. However,

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4 In the Soderberg method, the electrical current enters through rows of pins that is inserted into the carbon anode either horizontally or vertically, each making a specific type of the basic Soderberg technology. In this paper we however disregard this variation.
5 Again, there are several types of the Prebake method, depending on how the alumina is introduced into the reduction cell. We continue to disregard these fine differences.
6 It should be noted that the cost shares reported here are slightly different than those reported in, for example, King, (2001) and Gagné and Nappi (2000). This difference depends on our definition of total variable cost.
alumina use is governed chiefly by chemical laws at around 1.95 ton per ton of primary aluminium. Thus, there has been no measurable change in alumina input demands over the last decades.

Table 1. Average Cost Shares by Factor Input in Selected Regions

<table>
<thead>
<tr>
<th>Region</th>
<th>1995</th>
<th>2003</th>
<th>Anode and Bath mtrls</th>
<th>Electricity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Africa-Middle East</td>
<td>0.506</td>
<td>0.531</td>
<td>0.059</td>
<td>0.361</td>
</tr>
<tr>
<td>Asia</td>
<td>0.474</td>
<td>0.393</td>
<td>0.070</td>
<td>0.402</td>
</tr>
<tr>
<td>Western Europe</td>
<td>0.430</td>
<td>0.407</td>
<td>0.054</td>
<td>0.327</td>
</tr>
<tr>
<td>CIS</td>
<td>0.757</td>
<td>0.492</td>
<td>0.021</td>
<td>0.124</td>
</tr>
<tr>
<td>China</td>
<td>0.560</td>
<td>0.493</td>
<td>0.037</td>
<td>0.380</td>
</tr>
<tr>
<td>Eastern Europe</td>
<td>0.434</td>
<td>0.460</td>
<td>0.070</td>
<td>0.436</td>
</tr>
<tr>
<td>Latin America</td>
<td>0.462</td>
<td>0.438</td>
<td>0.087</td>
<td>0.385</td>
</tr>
<tr>
<td>Northern America</td>
<td>0.512</td>
<td>0.432</td>
<td>0.043</td>
<td>0.276</td>
</tr>
<tr>
<td>Oceania</td>
<td>0.520</td>
<td>0.494</td>
<td>0.044</td>
<td>0.310</td>
</tr>
</tbody>
</table>


The importance of electricity costs to the industry originates in its variability across smelters. According to Gagné and Nappi (2000) more than 60 percent of the variability in the total production costs of primary aluminium is due to the variability in energy costs across smelter location. Electricity tariffs in high cost regions/countries, such as part of Western Europe and China, are three to four times that of low cost regions such as the CIS-region and Canada (CRU, 2004). Table 1 reflects these differences; for smelters in China and Asia the share of electricity in total variable cost was between 42 and 48 percent in 2003, while for CIS-smelters the corresponding share was only 25 percent. The variability in electricity costs depends on the energy source used in power generation and the type of relationship/contract that prevails between utility and smelter. Smelters utilizing electricity from hydro power- or
low cost coal- or natural gas fired utilities regularly have a cost advantage, as do smelters using self-generated electricity. Several different types of long-term preferential contracts or contracts where the tariff paid is tied to the metal price are also common and contribute to the variability in electricity prices. Labour also constitutes a substantial cost factor for smelters, and its use largely dependent on local wage rates. However, higher staffing levels in regions with relatively low wages tend to be partially offset by the lower labour productivity, so the labour cost per ton of primary aluminium do not vary widely across the industry (King, 2001). We can see that for regions such as North America and Western Europe, labour constitutes a considerable share of variable costs, while in China this share is almost negligible.

The oil crises in the 1970s highlighted the importance of electricity costs to the industry. For example, the Japanese primary aluminium industry, once the second in the world and highly dependent on oil-generated electricity was rapidly dismantled in the aftermath of the oil price shocks. Aside from efforts to curb electricity costs by long-term contracts and greenfield investments in locations offering cheap energy, electricity use has seen a steady improvement due to improvement in existing processes and from brownfield investments in for instance; (a) increased size and life time of reduction cells improving both electricity efficiency and labour productivity; (b) increased current intensity and (c) improved operating practices and process controls. The combined effect of these improvements along with the ongoing switch from Soderberg to Prebake technology in brown- and greenfield investments has brought down electricity consumption considerably. Using global data, Table 2 displays a close to six percent industry-wide reduction in electricity use since 1990 and tracking back to 1980s the improvement is yet more considerable. It is also noteworthy that according to Bergsdal et al., (2004), in 1995 the average electricity use for Soderberg smelters are 16.6 MWh per ton of output, compared to around 13.3 MWh per ton for the very best greenfield Prebake smelters. This difference in electricity consumption partly explains the preference for the Prebake technology in greenfield investments and major conversion projects.

Our figures in Table 2 moreover show a surprising fall in labour productivity, contrary to, for example, Utigard (2004) which reports stunning improvements of more than 250 percent over the last two decades. The decreased productivity found here has likely to do with the lack of information concerning smelters located in the CIS-region prior to 1993. A number of Chinese smelters have also been continuously added to the CRU-database that underpins

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According to the IAI the average electricity use in 1980 was close to 17 MWh per ton of primary aluminium produced (IAI, 2006).
the data in Table 2. Both smelters in the CIS-region and in China maintain very high staffing levels compared to smelters in the west. The cover of Chinese smelters is still yet incomplete in the CRU database (if compared with the number of Chinese smelters listed by King, 2001).

Table 2. Capacity, Output and Input Use in Primary Aluminium Smelting 1990-2003

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Alumina (t/t)</td>
<td>1.937</td>
<td>1.937</td>
<td>1.937</td>
<td>1.937</td>
<td>1.939</td>
<td>1.939</td>
<td>1.940</td>
<td>1.940</td>
</tr>
<tr>
<td>Mhrs/t</td>
<td>11.6</td>
<td>13.1</td>
<td>14.6</td>
<td>13.7</td>
<td>14.6</td>
<td>13.6</td>
<td>17.2</td>
<td>17.1</td>
</tr>
<tr>
<td>Anode mtrl (t/t)</td>
<td>0.34</td>
<td>0.37</td>
<td>0.37</td>
<td>0.37</td>
<td>0.39</td>
<td>0.39</td>
<td>0.42</td>
<td>0.42</td>
</tr>
<tr>
<td>Bath mtrl (t/t)</td>
<td>0.027</td>
<td>0.028</td>
<td>0.029</td>
<td>0.028</td>
<td>0.023</td>
<td>0.022</td>
<td>0.025</td>
<td>0.025</td>
</tr>
<tr>
<td>Electricity KWh/t</td>
<td>14895.5</td>
<td>15048.2</td>
<td>14960.5</td>
<td>14919.7</td>
<td>14429.1</td>
<td>14311.5</td>
<td>14134.9</td>
<td>14030.7</td>
</tr>
</tbody>
</table>


Increases in labour productivity in smelters in the west with high wage rates have been considerable over the period, driven by increased mechanization, process controls and improved cell life leading to fewer replacements. According to King (2001) savings in manpower can be as important as savings in power cost for many smelters. If we consider anode materials use and its development, the figures in Table 2 again show falling productivity. We hold it likely that it is due to the same reason as with labour productivity, i.e., the inclusion of Chinese and CIS-smelters with less efficient process controls etc. Productivity developments in anode materials use are chiefly directed against increased recycling and reduction in material failures, something which overall has led to the reduction of net anode materials at state-of-the-art smelters. Finally, in primary aluminium smelting environmental concerns focus on two issues; (a) the release of greenhouse gases (GHG) and (b) the emission of (mainly) fluoride gases both within and outside the plant. The release of GHG belongs chiefly to the energy source used in electricity production and not to the smelter itself. In the latter case, the emission of fluoride gases, which is a potential workplace hazard and also causes damage to vegetation and ruminants feeding on it, large cuts have been achieved by the introduction of dry- and wet scrubbers. Furthermore, gaseous emissions are more easily collected and treated if the smelting process is enclosed. In Soderberg smelters the reduction cells normally are open to the atmosphere thus allowing fluoride and other gases to escape (if no special efforts have been undertaken to capture them). Prebake smelters use
hooded reduction cells in which gases cannot escape but is transported to a scrubbing system. This difference is likely to contribute to the ongoing shift from Soderberg to Prebake technologies in the industry. Since efforts to curb emissions do not directly affect productivity and is likely to increase the cost of smelters they are usually introduced only if forcing regulation and other government interventions are in place. Thus, there are substantial deviations across smelters in emission controlling equipment applied due to differences in the local “intensity” in environmental regulation. For instance, up until 1999 several greenfield smelters in China were started using Soderberg technology (King, 2001), and a huge number of Chinese smelters lack any scrubbing system whatsoever (CRU, 2004). Overall, King (2001) estimates that at the end of the 1990s, 81 percent of western smelter capacity had dry scrubbing systems installed, compared to only 17 percent of eastern capacity (i.e. smelters in the CIS, China and so forth). To sum up, productivity improvements have been achieved in the industry, especially concerning electricity usage. Labour productivity is likely to have improved also, at least at western smelters. However, the bulk of these improvements seems to have come due to improvements at smelters located in western industrialized economies, locations often associated with high factor costs and more stringent regulations. Productivity development - at least anecdotally evidence points in this direction - has been slower over time in, for example, China and to some extent the CIS-region. Thus, the foundation for further investigating differences in productivity changes across regions seems to be laid out.

**METHODOLOGICAL FRAMEWORK**

The Malmquist productivity index approach (Malmquist, 1953) allows us to distinguish between changes in productivity due to changed efficiency and/or technological changes. In its most elementary setting total factor productivity (TFP) is defined as;

\[
TFP = \frac{y^{t+1}}{x^{t+1}} \cdot \frac{y^t}{x^t} \quad [1]
\]

where \(y\) is output and \(x\) is a vector of inputs at two consecutive time periods \((t \text{ and } t+1)\). The productivity measure in [1] can be written as the ratio between two distance functions. Specifically, the distance function of a production unit \((D_0)\) in time \(t\) in relation to the technology \((F(t))\) in the same time period can be written as;
where \( \theta \) is the objective to be minimized; in this case the amount of production factors used to produce a given amount of output, given the technology, \( F(t) \). This distance function measures the minimum reduction of inputs that is necessary in order for the production unit to be on the efficient frontier in time period \( t \). The above concept allows us to analyze productivity changes between two time periods - using time \( t \)'s technology as a reference - with the following Malmquist productivity index;

\[
D(t; x_{t+1}, y_{t+1}) = \min(\theta : (y_{t+1}, \partial x_{t+1}) \in F(t))
\]

The interpretation of the input based Malmquist index is that values greater than one indicates that productivity in period \( t+1 \) has improved compared to the reference period, and if the index is less than one the productivity has fallen in the latter period.

The Malmquist index of productivity change can be further separated into a catching up effect that shows if a unit is moving closer or further away from best practice (i.e., change in relative technical efficiency between the periods) and a front-shift effect which shows if best practice is improving, deteriorating or stands still (i.e., productivity changes due to technology change). The separation is done by calculating indices for two successive years based on the technology in each period, and then calculate the geometric mean of these two indices (Färe and Grosskopf, 1996). It is then possible to divide the Malmquist index into a catching-up effect and pure technological effect in the following way (Shestalova, 2003, Färe, 1994):

\[
M(t; x_{t+1}, y_{t+1}, x', y') = \frac{D(t; x_{t+1}, y_{t+1})}{D(t; x', y')}
\]

where the first ratio represents the catching up effect and the second term measures the pure technological effect on productivity. The interpretation of these two effects is the equivalent to that of the Malmquist index above. In other words, TFP change can be decomposed as:

\[
M(t; x_{t+1}, y_{t+1}, x', y') = \frac{D(t; x_{t+1}, y_{t+1})}{D(t; x', y')} \frac{D(t; x_{t+1}, y_{t+1})}{D(t; x_{t+1}, y_{t+1})} [4]
\]

\[8\] The resulting Malmquist productivity index is the geometric mean of a Laspeyre-type index using technology at time \( t \) as a base and a Paasche-type index using technology of time \( t+1 \) as a base.
Change in TFP = Technical Efficiency Change * Technical Change
(Catching-up effect) (Frontier effect) [5]

As can be seen from equation [4], the Malmquist index consists of four distance functions; $D_t^e(x, y')$, $D_t^{e+1}(x^{e+1}, y^{e+1})$, $D_t^e(x^{e+1}, y')$ and $D_t^{e+1}(x', y')$. The first two concern the measurement within the same time period, while the two last are for the intertemporal comparison. These measures can, given access to suitable panel data, be calculated by DEA-like linear programs (Färe, 1994). Generally, using DEA-techniques to calculate efficiency and the Malmquist indices has the advantage that no prior assumption about the functional form or the underlying production technology has to be made, except for returns to scale (see below). A number of specific ways to compute the Malmquist indices by DEA exists. Färe et. al. (1994) utilize a radial DEA-model to make the computation. However, the radial model suffers from one shortcoming; the neglect of input slacks. Thus, in our computation we have opted for the non-radial measures developed by Tone (2001, 2002). Using this measure, the efficiency of a production unit $(x_0, y_0)'$, where $(s = t, t+1)$ with respect to the evaluator set, i.e., its competitors $(X,Y)'$ and $(t = t, t+1)$ is evaluated with the following linear programming problem(s);

$$D_t^e((x_0, y_0)') = \min_{\lambda, \delta} 1 - \frac{1}{n} \sum_{i=1}^{n} \frac{\delta_i}{x_{i0}}$$  [6]

Subject to:

$$x_0 = X' \lambda + \delta$$

$$y_0 ' \leq Y' \lambda$$

$$L \leq \epsilon' \lambda \leq U$$

$$\lambda \geq 0, \delta ' \geq 0$$

where the vector $\delta ' \in R^n$ represents the input slacks to be minimized and $X' = (x_1', ..., x_n')$ and $Y' = (y_1', ..., y_n')$ represent observed input vectors and output scalars. Hence, the scalar $\theta_j$ in equation [2] corresponds to $1 - \delta_j / x_{ij}^*$ in equation [6]. A further assumption must be made about the returns to scale prevailing before solving the LP-problems in [6]. Here we impose variable returns to scale (VRS) overall, i.e. $(L, U) = (1, 1)$, which is in line with for example the work by Burgess and Wilson (1995) on hospital productivity. This assumption is further justified since many capital intensive industries like primary aluminium smelting
demonstrates increasing returns to scale. Indeed, Blomberg and Jonsson (2006) show that only about 5 percent of the smelters in their sample operated at constant returns to scale and the rest under increasing returns.  

Two caveats should be recognized before proceeding. First, there are disagreements in the literature whether the Malmquist index provides accurate measurement of TFP under the assumption of VRS (e.g. Grifell-Tatje and Lovell, 1995, see also Maniadakis and Reed, 1997 for a review of the debate and some remedies). The matter seems most important if the technical efficiency part of equation [5] is to be further decomposed into scale efficiency and ‘pure’ technical efficiency. We will however not attempt such decomposition here.

Second, when evaluating the within scores $D^t_0(x^t_0, y^t_0)$ and $D^{t+1}_0(x^{t+1}_0, y^{t+1}_0)$ there are two potential schemes, ‘inclusive’ and ‘exclusive’. Inclusive implies that when evaluating the unit $(x_0, y_0)^t$ with respect to its peer group $(X, Y)^t$, the unit is always included in the $(X, Y)^t$. Thus the score cannot exceed one. In the exclusive scheme, the unit is removed from peer group resulting in a score potentially greater than one. The intertemporal comparisons $D^t_0(x^{t+1}_0, y^{t+1}_0)$ and $D^{t+1}_0(x^{t}_0, y^{t}_0)$ naturally applies this exclusive scheme, and with non-radial DEA-models, the software package used here (DEA-SolverPRO), the exclusive scheme is also excluded in the within comparisons. If an input-oriented model is applied and if VRS is imposed, it may occur that that the intertemporal part of the LP-problem in equation [6] has no solution if there exist $i$ such that $y^t_{i0} > \max_j \{y^t_{j0}\}$. To overcome this problem the DEASolverPRO software assigns the value 1 to all infeasible objective values and indices in the LP-problem. Furthermore, under the exclusive scheme when the unit is removed from the peer group, the within comparison also might lack a feasible solution even for the case where $s=t$. In this case, equation [6] is modified such as;

---

9 One caveat with this approach should be mentioned. With a variable returns to scale technology and only a few units of small or large size there is a risk that these “extreme” units will appear fully efficient simply due to the lack of comparable truly efficient peers in the observed data set. If we instead assume a constant returns to scale technology this enables us to compare “extreme” sized companies with “average” sized companies, and thus avoid making the “extremes” appear (artificially) efficient.

10 Solving the LP-problem in [6], the DEASolverPRO software encountered one infeasible solution. Hence, out of 118 smelters the software assigned the value 1 to the objective values and indices for that particular smelter.
\[ D_0^f((x_0, y_0)^t) = \min_{\lambda, \delta} \quad 1 + \frac{1}{n} \sum_{i=1}^{n} \delta_i \]

\[ x_0^* = X^* \lambda - \delta^* \]

and where all other constraints remain. This modification is due to Tone (2002) and is a ‘super-efficiency’ measure of slacks.

**DATA**

To enable calculation of TFP and the Malmquist indices described above we need input and output data for the primary aluminium industry. In this paper we have derived the necessary data from the Aluminium Smelter Cost Database, a proprietary database provided by CRU International Ltd. CRU collects the data from several sources such as questionnaires, interviews, plant visits, published information, industry contacts and CRU’s own estimates (see CRU, 2004 for further information). Using consultancy data to make broad international comparisons might give rise to questions about the quality of the data and certainly demands caution. As we wish to estimate the TFP at the individual smelter level to enable various aggregations in the later analyses, few other options however remain. Furthermore, CRU’s large client base within the metal industries and its long experience in undertaking the collection and systemization of plant level data cause us to judge the data as reliable.

The CRU database claims to cover close to all smelters globally. However, we have opted here to include only the 118 smelters operative under the entire ten year period covered in the study, i.e. from 1993-2003.\(^\text{11}\) Thus, we have omitted a large portion of Chinese smelters that either has started up or have been included in the CRU data set during the period. Moreover, all smelters that have been closed down over the period have consequently been left out. It is likely that this omission may lead us to overestimate the productivity development since it is probable that de-activated smelters were the least efficient ones.

The inputs included in this study are alumina, labour, anode related inputs, bath materials and electricity. Basic statistics for the sample of smelters for two years, 1993 and 2003 are shown in Table 3. Taken together, the chosen inputs make up approximately 85 percent of the variable smelter site operating costs.

\(^{11}\) To maintain the confidentiality of the CRU proprietary data, smelters will never be named; consequently all results pertains only to groups of smelters, i.e., by geographical region or technology.
All input measures refer to activities belonging to the smelter process itself i.e., the pot line. Therefore the inputs used in other auxiliary production stages such as the bake furnace and cast house facilities are excluded. This omission is made to increase the compatibility of smelters. For example, some Prebake smelters do not have their own anode production capacity but instead buy the anodes from other smelters, making comparisons more complicated if the bake furnace stage were included in the analysis. Moreover, variable costs like maintenance and costs for pot relining were also excluded from the study.

**Table 3. Basic Statistics for Selected Years**

<table>
<thead>
<tr>
<th></th>
<th>Output (1000s tons)</th>
<th>Alumina (t/t)</th>
<th>Labour (Employees)</th>
<th>Anode mtrl (t/t)</th>
<th>Bath mtrl (t/t)</th>
<th>Electricity (KWh/t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>172.0 206.0</td>
<td>1.94 1.94</td>
<td>923.9 1055.1</td>
<td>0.50 0.49</td>
<td>0.04 0.03</td>
<td>14908.4 13995.2</td>
</tr>
<tr>
<td>Median</td>
<td>126.3 166.8</td>
<td>1.94 1.94</td>
<td>604.0 632.2</td>
<td>0.48 0.49</td>
<td>0.04 0.02</td>
<td>14745.0 13803.7</td>
</tr>
<tr>
<td>Min</td>
<td>10.0 6.0</td>
<td>1.89 1.92</td>
<td>80.0 20.5</td>
<td>0.41 0.41</td>
<td>0.02 0.01</td>
<td>12999.0 12580.5</td>
</tr>
<tr>
<td>Max</td>
<td>810.0 930.8</td>
<td>2.10 1.96</td>
<td>9345.4 6331.2</td>
<td>0.86 0.67</td>
<td>0.08 0.08</td>
<td>18500.0 17738.8</td>
</tr>
<tr>
<td>Stdev</td>
<td>125.6 151.0</td>
<td>0.02 0.01</td>
<td>1202.7 1159.2</td>
<td>0.08 0.05</td>
<td>0.02 0.01</td>
<td>1184.0 929.6</td>
</tr>
</tbody>
</table>


One advantage of applying DEA-methods when solving the LP-problem in equation [6] is that the resulting scores are independent of the values of which the inputs are measured in (Cooper et.al., 2000). Hence, there is no need to re-calculate the values of inputs on the same basis of measurement. All physical inputs are measured in tons per finished output (i.e. tons of primary aluminium), with the exception of labour which is measured as the number of pot line (process) employees. Electricity use is measured as the use in kWh per ton of finished aluminium in the electrolytic process itself, thus excluding any auxiliary electricity use in the plant. Finally, smelter output is measured in thousands of tons of primary aluminium.

Two issues should be noted. First, the measures of anode and bath material use represent aggregated sums of several different input and cost components that together make up the anode and bath material categories. Second, as earlier discussed in some studies (e.g., Gagné and Nappi, 2000; Bye and Forsund, 1990), alumina is treated as a shadow input to output motivated by the low variability in use and thus excluded from estimations in these

12 The Carbon/Anode input category is a weighted average of purchased anodes, petroleum coke, pitch material and packing coke. The Bath material input category is a weighted average of aluminium fluoride and cryolite.
studies. The high cost share of alumina and the fact that use still varies between 1.92 to 1.96 tons per ton of output, makes us believe that it is still motivated to include alumina in the calculations.

Finally, when we solve the linear programming problems in equation [6], we use the entire sample of 118 smelters. When presenting the result we first divide the smelters across technology, i.e., Soderberg, Prebake or smelters using a mix of the two technologies, to gain information to be used in the discussion on regional variations in productivity developments. Second, we present the results divided on a regional basis. Any such “lumping” together of smelters located in different nations must be based on a weighting of the cost of aggregation, i.e., loosing detail and benefits in the form of generality. For instance, there are differences in tariffs levels within the Western European region, where Norway with smelters utilizing hydropower generated electricity enjoy relatively low tariffs compared to smelters in the central parts of Western Europe. Another example is that is likely that there are national differences in policies etc. facing the industry in such a wide area as the Africa-Middle East region. However, we still maintain that aggregating smelters in the regions defined below is worthwhile.

EMPIRICAL RESULTS

General Total Factor Productivity Change in the Primary Aluminium Industry

When solving the LP-problem in equation [6], we get the annual change in TFP. To provide more perspective on the long term productivity development, we construct a cumulative index as the sequential multiplicative sum of the annual indexes. The index is interpreted as percentage changes. TFP-change, as measured by the Malmquist index, consists as previously discussed of two components. The first component, technical change, describes the movement of the production front itself due to the application of new technologies, changed practices and so forth. The second component, the effect from changes in technical efficiency, measures whether a smelter has become more or less efficient over time compared to its best practice competitors, i.e. relative to the production frontier. Figure 1 displays the cumulative change in TFP, i.e., the Malmquist index, and its components for the entire primary aluminium industry with 1993 as the base year.

We can see that over the period 1993 to 2003 the global primary aluminium industry improved its TFP by close to ten percent. Technological change seems to be the main driving force behind this improvement. Over the entire period the production frontier shifted outward.
by approximately seven percent. Technology seems to have improved at a rapid pace in the first four years up to 1997, improving by five percent. This change was partially balanced by a slight decrease in the technical efficiency index. This indicates that the distance between the average production of the smelters in our sample and the best practice smelters increased. After 1996, the industry went through a brief period of technological regress stretching to 1998 when the technological front backtracked by 2 percent, meaning that the TFP change of the best practice smelters slowed. It should be noted that technological regress in frontier analysis is an empirical issue, and may involve a combination of factors such as changes in practices, institutional changes, as well as changes in production techniques (Ma et al., 2002). Technological regress should normally not be interpreted as production techniques once known have been forgotten (Ibid.)

As the technology development leveled off at the best practice smelters in 1996, smelters not on the frontier caught up with their most efficient competitors. The indexes for technological change and technical efficiency dispersed once more over the remaining period, as technological change gained pace once more after 1998. From this year and up to the end of the period in 2003 the distance between the smelter on the front, i.e., the best practice plants and the average smelter increased as efficiency improvements lagged behind. This counter wise movement in the two indexes is probably caused by the presence of a time lag between the measures taken by the best practice smelters, i.e., industry leaders adapting technological and managerial innovations quickly and the followers not on the frontier (Ma et

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13 Mean of all smelter units globally.
al., 2002). When the frontier shifts swiftly outwards, the relative efficiency of the followers trails even more until the pace of innovations slows, giving them the chance to catch up. The above result is an indication that since technological change has dominated TFP-development, there are fewer barriers to innovation and diffusion than there are institutional barriers, managerial inefficiency and so forth, factors that are more likely to be determined locally.

**Total Factor Productivity Changes per Technology**

As discussed earlier, there is a tendency for the different smelter technologies to be geographically concentrated to different parts of the world. In order to gain information for the continuing discussion of regional differences in TFP-development we will briefly discuss potential differences in TFP across smelters using Soderberg, Prebake and a mix of the two technologies. One caveat should be mentioned. As the CRU database used here only contains information on technology for the last year, 2003, we have assumed that each smelter in the set have used that year’s technology for the entire period. For example, this means that some smelters may have started out using only Soderberg technology and sometime over the period 1993-2003 either changed technology entirely or ended up as a mixed technology smelter.\(^\text{14}\)

Figures 2a-c displays the development of the components of productivity change divided by type of smelter technology. Three things could be noted. *First*, for all three technologies, most of the TFP-improvement comes from the production frontier shifting outwards, i.e., technical change. The development mirrors that shown above for the entire industry, with rapid development of technical change in the beginning of the period and then decline and eventually renewed technical improvement, which confirms that this development is caused by some general factor affecting the entire industry. *Second*, both technological change and (especially) the efficiency change display more year to year variation for pure Soderberg smelters. The technical efficiency effect is with the exception of 1994-1998 almost as strong as the technological change effect for Soderberg smelters. A perhaps speculative conclusion from this is that the Soderberg type of technology has drained most of its potential technological improvements. Another possibility is that the conversion plans to Prebake technology at smelters currently operating with Soderberg technology are gaining pace due to the latter technologies superior efficiency and environmental performance. If smelters plan to make a major overhaul in the technology used or perhaps closing down Soderberg capacity in the near future, it is likely that the focus on productivity gains will mainly be channeled

\(^{14}\) The reverse – a change from Prebake to Soderberg technology – is of course also possible but is highly unlikely.
through improvements in the use of current technology, i.e., moving closer to the frontier. Investments in pure technological development will on the other hand be withheld.

Figure 2a-c. Productivity Change per Technology

- 18 -
Third, smelters using a mix of the two technologies show a more rapid TFP-growth than smelters using only one of the two technological alternatives. The rapid development for mixed technology smelters can allegedly be explained by the group being made up of what once were “pure” Soderberg smelters being (partially) converted to Prebake technology using state of the art equipment during the period, thus driving technological change. Such major overhaul may also imply that the smelters are prioritized in other ways such as improvements in process controls and management practices explaining the high rate of efficiency change.

**Total Factor Productivity Changes per Region**

In this section we investigate the impact of location on productivity development. At the beginning of the paper we raised the hypothesis that the TFP-development should differ across regions. Furthermore, smelters located in stagnant and high cost regions, mainly in the western hemisphere should exhibit higher productivity growth than smelters in expanding regions. The productivity change in the west should mainly come about through improvements in efficiency due to the lack of major investments in the form of greenfield smelters or major capacity increases at existing smelters. Table 4 presents the ten year average productivity growth divided per region. We clearly find regional variations in TFP and its components.

<table>
<thead>
<tr>
<th>Region</th>
<th>Technical Efficiency Change</th>
<th>Technological Change</th>
<th>TFP</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>1.002</td>
<td>1.078</td>
<td>1.080</td>
</tr>
<tr>
<td>CIS</td>
<td>0.992</td>
<td>1.071</td>
<td>1.054</td>
</tr>
<tr>
<td>North America</td>
<td>1.036</td>
<td>1.085</td>
<td>1.127</td>
</tr>
<tr>
<td>Latin America</td>
<td>1.044</td>
<td>1.061</td>
<td>1.107</td>
</tr>
<tr>
<td>Oceania</td>
<td>1.058</td>
<td>1.065</td>
<td>1.126</td>
</tr>
<tr>
<td>West Europe</td>
<td>1.018</td>
<td>1.069</td>
<td>1.089</td>
</tr>
<tr>
<td>East Europe</td>
<td>1.102</td>
<td>1.064</td>
<td>1.169</td>
</tr>
<tr>
<td>Africa &amp; Middle East</td>
<td>1.027</td>
<td>1.082</td>
<td>1.112</td>
</tr>
<tr>
<td>Asia</td>
<td>0.965</td>
<td>1.124</td>
<td>1.102</td>
</tr>
<tr>
<td>Global average</td>
<td>1.023</td>
<td>1.077</td>
<td>1.101</td>
</tr>
</tbody>
</table>

15 The average represents the mean of TFP-change (and its components technical efficiency and technological change) of all smelter units in a particular region.
The global average productivity change is just above ten percent over the period, out of which approximately three quarter’s stems from technological change. North America, the Oceania-region and especially Eastern Europe exhibit higher than average TFP-growth. Smelters in Eastern Europe could thus by 2003 produce almost 17 percent more primary aluminium using the same amount of production factors as they did in 1993. Most of this was achieved by a strong surge in smelter efficiency which improved by more than ten percent over the period. A possible explanation to the efficiency improvements is the rapid change toward a market economy and the adoption of market supporting institutions. Yet another explanation to the observed efficiency improvement is the dip in production experienced by some of the smelters in the midst of the period, especially smelters located in the Balkan area. As the Balkan wars ended and more normal production conditions resumed these smelters rapidly diminished the distance to their competitors on the front. Smelters in both North America and the Oceania region have become substantially more efficient over the period. North American smelters have also gone trough above average technological change. A potential explanation to the efficiency improvements is that high and rising labour costs have triggered both implementation of labour saving technology and practices including better training etc.\textsuperscript{16}

Three regions in particular seem to be lagging behind, China, the CIS-region and Western Europe, all with TFP-growth rates below the global average. Smelters in the CIS-region are the worst ‘underperformers’ with only a five percent productivity improvement over the period. Smelters in the CIS-region actually became less efficient by almost one percent over the period according to the catch-up index. Also China showed almost no efficiency improvement over the period. In China in particular, the almost explosive expansion of capacity over the period in combination with subsidies in the form of VAT-rebates likely have made some smelters content to ensure survival rather than focus on competitiveness and productivity (CRU, 2004). Furthermore, not all of the rapid expansion in Chinese capacity over the last two decades has been driven by demand growth or profit objectives. Some smelter projects have gained support from local authorities aiming at regional development; projects often disapproved by the central government due to among other things China’s poorly functioning electricity markets with frequent blackouts (Ibid.). Both China and the CIS-region have very low costs for labour and the CIS has the world’s

\textsuperscript{16} Smelters in the US have the highest labour costs per hour in the world. Labour costs in Oceania are also above the world average (CRU, 2004). Mirroring this is the high labour productivity in these regions. CRU (2004) reports that it takes on average 5.5 man-hours to produce one ton of primary aluminium in Oceania compared to 28.6 man-hours in China.
lowest electricity tariffs which might further hamper the incentive to become more productive.

The TFP-change at smelters in Western Europe was also well below the global average. As Western Europe is an essentially stagnant and high cost region where little investment in capacity expansion has been undertaken during the last decade, we expected the focus to be on improving technical efficiency. Surprisingly smelters in this region improved efficiency by less than two percent over the period. Most of the TFP-enhancement came from technical change, even that also was below world average. One suggestion is that the bulk of investment undertaken at smelters in Western Europe has been directed at emission control and so forth, which do not directly improve productivity. Another suggestion is that smelters in this region has been exposed to high factor costs for electricity and labour for a considerable time; thus a lot of productivity improvements have already been undertaken.

The three last regions, Latin America, Africa and the Middle East and Asia all have had TFP development just above the global average. The two latter regions have seen capacity and production grow rapidly over the period. Thus, with a lot of green- and brownfield investment the rapid pace of technical change of more than twelve and eight percent respectively should not surprise. The drop in technical efficiency in Asia is, partly caused by the same factors as in China; the focus has been on capacity expansion and not on becoming efficient with existing technology. In Latin America finally, most of the regions’ capacity expansion came in the 1980s. During the last decade capacity expansion has been much slower, and possibly the focus thus have turned to enhancing efficiency instead.

Next we turn to study the time path of TFP-change across regions. Figures 3a-i display the cumulative productivity development for the different regions. The patterns for the different regions revealed in Figure 3a-i largely mimic the pattern’s described above with periods of rapid technical change breeding increased inefficiency as some smelters fall further behind, followed by phases of slower technical change and inefficient smelters catching-up with the best practice smelters. One notable exception from this general pattern is the development in the Oceania region, where both technical- and efficiency change trace each other tightly. When the front moves due to technical innovations, less efficient smelters in Oceania quickly improve their performance. A possible explanation to this phenomenon is that Oceania is a comparatively small and homogenous region with relatively strong infrastructure for primary aluminium production. Hence, efficiency improvements may quickly be implemented.
Productivity Indices

- Technical Efficiency Change
- Technical Change
- Total Factor Productivity (Malmquist Index)

a. Cumulative Productivity Change in China

b. Cumulative Productivity Change in CIS

c. Cumulative Productivity Change in North America
d. Cumulative Productivity Change in Latin America

e. Cumulative Productivity Change in Oceania

f. Cumulative Productivity Change in Western Europe
Productivity Indices

Technical Efficiency Change
Technical Change
Total Factor Productivity (Malmquist Index)

Figure 3a-i. Productivity Change per Region

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Considering the development in other regions, we can see that the smelters in China and the CIS-region have experienced a weak development over the period and achieved a relatively weak four to five percent overall growth as shown by their respective TFP-index. Their technological development has been slow, but even more striking is their very weak, even over some periods negative, technical efficiency effect, confirming the discussion above. Hence, smelters in these regions move further away from the frontier over almost the entire period, i.e., they become less efficient in each time period at applying the current technology. This result may be due to institutional factors such as insufficient competitive pressure. For instance, labour productivity in both regions is lagging behind high wage regions such as Oceania and Northern America. In China it takes approximately five times the man-hours to produce a ton of primary aluminium (CRU, 2004). Another region with similar feeble development is Latin America. However, here smelters started to catch-up significantly with the frontier at the millennium shift. Considering western smelters, those in North America and Oceania shows strong overall TFP-growth at around 13-14 percent. In North America, technological change seems to be the driving force. Smelters in Western Europe, however, show a slower growth in TFP, achieving approximately seven percent. Contrary to our expectations, efficiency improvements in particular seem modest at Western European smelters. Western Europe is a high cost region where little capacity has been added in the last decades; hence most TFP-gains should have come through focusing on improving management, operating practices and other incremental improvements allowing for enhanced efficiency of smelters. Whether the comparatively slow development of such factors depends on institutional factors, lack of competition and so forth is difficult to determine, but it underlines the difficulties facing the industry in large parts of the region.

Smelters in Eastern Europe have had very strong productivity improvements. Most of this improvement originates in the first half of the period, when it seems that the application of better practices to existing technologies was the main driving force behind productivity development, as shown by the surge in the technical efficiency index. This confirms our previous discussion of the region’s development. Asia, finally, has had a very rocky development, with productivity “explosions” in, for example, 2001-2002 followed by sharp declines in the following year.

Given our previous findings that Soderberg type smelters performed fairly well as a group, the slow TFP-development in China and the CIS-region where the Soderberg technology still is applied at a huge number of smelters is somewhat puzzling. One possible explanation is that Soderberg smelters located in other regions with higher overall TFP-
change have experienced sufficiently strong productivity improvements to elevate the entire index for Soderberg-type smelters in Figure 2a.

Summarizing our empirical findings, the overall TFP-index shows that the primary aluminium industry is approximately ten percent more productive at the end of the period compared to at the beginning. Smelters using both Soderberg and Prebake technology display the most rapid development, possibly due to relatively recent refitting and modernization processes. Pure Soderberg smelters also show rather rapid productivity development, mostly due to using current technology better, however with significant variation over time in the technical efficiency index. Prebake smelters show a rather strong technological shift trend, meaning that the main force in the overall development has been shift in the production frontier due to better technology, and to lesser extent using the current technology more efficiently. Finally, productivity trends across regions show that China and the CIS-region lag behind, especially in using existing technology, while smelters in Eastern Europe, North America and the Oceania region show strong productivity developments.

A SUMMARY OF THE MAIN FINDINGS
The purpose of this paper has been to evaluate the total factor productivity (TFP) development of the global primary aluminium industry over the time period 1993-2003, using a Malmquist-index approach. The main hypothesis posed was that due to differences in factor costs and thus competitive pressure there should be variations in TFP over different smelter locations.

As smelters in many western nations, such as in the US and in large parts of Western Europe, have come under increasing pressure from mounting electricity and labour costs, some of the increasing competitive disadvantage may be alleviated by improving factor productivity. Since little new capacity has been installed in these regions for the last one or two decades, most of factor productivity development can be expected to come from improvements in the efficiency in applying existing technology. Contrary to this, in regions where capacity additions have been substantial, technological change was expected to dominate the TFP-development. The results, however, only partially confirm this a priori view. North American smelters and smelters in the Oceania region, both relatively high cost regions where capacity either has expanded relatively slowly or even started to fall, have experienced above-average TFP-growth. In particular concerning smelters in North America, this growth has come about largely by technical change and not by progresses in efficiency. In Western Europe, another stagnant, high cost location, TFP-change has been below the global
average and also here the bulk of what is of factor enhancements have been realized by technical change.

Concerning regions where capacity has expanded during the period, such as in China, the CIS, and Africa and the Middle East the pattern is somewhat clearer. Most of TFP-improvements have come by technical change, i.e., a movement of the efficient front over the period, which should be expected as assumedly the best technology is used when undertaking greenfield investments. To a lesser extent, efficiency improvements have contributed to TFP-growth in these regions. In CIS efficiency has even fallen over the period as a whole and at Chinese smelters the efficiency development has also been negative for parts of the period.

Finally, we argued initially that the different smelter technologies tend to be concentrated to particular regions. For instance, according to King (2001) most of the remaining Soderberg capacity is found in Eastern countries, in particular in China and the CIS-region, where TFP-growth has been comparatively weak. Thus, the potential difference across smelter technologies should be evaluated to strengthen the regional analysis. However, the result showed that Soderberg smelters did not in general trail very far behind Prebake-technology smelters in TFP-growth over the period. One possible explanation is that the remaining Soderberg capacity in the west have experienced strong enough TFP-growth to obscure the weak TFP-growth in regions where this technology still dominates.

REFERENCES


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Abstract: The purpose of the paper is to estimate the degree of ex post factor demand flexibility in the primary aluminium industry in Western Europe and the Africa-Middle East (AME) region. We use a Translog variable cost function model, which is estimated employing a panel data set at the individual smelter level over the time period 1990-2003. The empirical results suggest that the null hypothesis of zero ex post factor substitutability can be rejected. Overall aluminium smelters in the AME region show evidence of higher short-run own- and cross-price elasticities than their competitors in Western Europe, at least when it comes to labour and electricity demand. Western European smelters can however more easily switch between the material input and electricity. The results also suggest that in both regions the demand for electricity has over time become less sensitive to short-run price changes, while the substitution possibilities between labour and material have increased but only in the AME-region. The liberalization of the Western European electricity markets in combination with the rigid labour markets in this part of the world suggest that the shift in production capacity from the western world to the AME-region as well as China may continue.

Key words: aluminium, short-run price elasticities, factor demand flexibility, Translog cost function, Western Europe, Africa and the Middle East.

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INTRODUCTION

Capital intensive industries such as the metal, mining, electricity and pulp and paper sectors are often assumed to be dominated by so-called putty-clay technologies. In other words, *ex ante*, prior to the construction of the respective facilities, there exists a clear possibility for substitution between all factors of production. However, once a plant’s design is fixed in terms of a specific capital equipment, the scope for substitution is substantially reduced. Thus, *ex post* the elasticities of substitution may be very low or even zero. Increased factor demand flexibility *ex post* has however often become increasingly important, especially in the case of inputs for which prices tend to fluctuate a lot over time. One example is the electric power sector, which in response to the oil crises in the 1970s substantially improved its short-run fuel flexibility (e.g., Söderholm, 2000). In general the ability to exploit short-term price differentials gives plant-owners increased negotiating power and it places a ceiling on factor prices aiding plants in minimizing costs.

The purpose of this paper is to estimate the degree of *ex post* factor demand flexibility in the primary aluminium industry in Western Europe and the Africa-Middle East region. The analysis will be done using a Translog variable cost function model, which we estimate using a panel data set (provided by CRU Intl.) at the individual smelter level over the time period 1990-2003. The model is used to estimate short-run own- and cross-price elasticities of factor demand in the industry, and permits tests of: (a) the null hypothesis of zero *ex post* substitution; (b) regional differences in factor flexibility; and (c) whether smelters of more recent vintages (i.e., built after the first oil crisis in 1973/74) are more flexible in their input choices than are older ones.

The chosen focus on the aluminium sector is motivated for a number of reasons. Factor substitution possibilities are claimed to be very limited *ex post* the investment decision (e.g., Bye and Forsund, 1990). On the other hand, we argue, relatively recent developments in the industry may imply an increasing pressure to increase this flexibility. This is due to the liberalization of electricity markets and the important role of electricity in the aluminium smelting process. While material costs (e.g., alumina, bath materials etc.) – usually the most burdensome cost factor – do not vary much between smelters, electricity costs do.¹ Thus, access to cheap electricity is of pivotal importance for the competitiveness of a primary aluminium smelter operation. With the liberalization of electricity markets and new policy instruments (e.g., emissions trading for carbon dioxide) aluminium smelters in Western

¹ Gagné and Nappi (2000) estimate that more than 60 percent of the differences in aluminium’s total production costs are due to the variability in electricity costs across smelters and locations.
Europe are however facing important challenges. A vast majority of the smelters in Western Europe has historically relied on preferential long term contracts with power generating utilities (Kirchner, 1988). However, these are now about to expire, and there are indications of increasing difficulties in renewing or prolonging the contracts with energy suppliers (Commission Staff Working Document, 2006). Moreover, although the liberalization of energy markets in Western Europe brought with it some initial improvements in electricity tariffs for large industrial users, the trend has since then been reversed and industrial tariffs have increased significantly since 2001 and are also likely to become more volatile (Ibid).

Figure 1 shows the declining share of primary aluminium output in Western Europe over the period 1990-2003 and contrasts this development to the one experienced in the Africa-Middle East (AME) region. The average electricity tariff in the AME-region has declined over the last decade and a half, at the same time as the region’s share of world output has nearly doubled. Although electricity tariffs have declined somewhat also in Western Europe, the tariffs remain at a substantially higher level. In combination with relatively unfavourable labour costs and the claimed putty-clay character of the primary aluminium industry this illustrates that the Western European aluminium industry is under severe pressure.

Figure 1. Electricity Tariffs and Share of World Output of Primary Aluminium for Western European and Africa-Middle East Smelters

In this paper we test to what extent the short-run factor demand flexibility differ across these two regions, one stagnating and one expanding. It is reasonable to hypothesize that in Western Europe – with many existing, old smelters at place – an efficient strategy to meet the

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2 The European Commission estimates that between 2005 and 2006 the share of smelters in Western Europe with long term contracts have declined from over 92 percent to just over 62 percent, and a further decline to somewhere below 30 percent in 2011 is to be expected (Commission Staff Working Document, 2006).
new market conditions for electricity could be to increase the industry’s flexibility to respond to price changes. If this turns out not to be the case, and if the AME-region appears to exhibit greater factor flexibility, this may provide one explanation (out of many) for the meagre performance of the Western European primary aluminium industry. In the paper we also investigate whether the first oil crises in 1973/74 brought with it a technical change in the industry towards greater flexibility in factor – and in particular electricity – use, and whether exogenous changes in technology has changed the relative use of input factors in the two regions.

Previous economic studies on the technology of the aluminium industry (e.g., Bergsdal et al., 2004; Bye and Forsund, 1990; Førsund and Jansen, 1983; Gagné and Nappi, 2000) have not paid much attention to the issue of short-run factor flexibility. Still, exceptions include Lindquist’s (1995) and Larsson’s (2003) investigations of Norwegian primary smelters, which test for the presence of short-run factor input substitution. However, these only focus on the Norwegian industry and on early time periods (1972-1990 and 1972-1993, respectively), and do therefore not consider neither regional differences nor the impact of plant vintages.

A SHORT RUN MODEL OF PRIMARY ALUMINIUM PRODUCTION

Primary aluminium is produced in an aluminium smelting plant using the main inputs alumina ($A$), electricity ($E$), labour ($L$) and various materials ($M$) such as carbon anodes and bath materials, and finally production capital ($K$). The output ($Q$) of primary aluminium from a representative smelter can thus be represented by a general aggregate production function of the following form:

$$ Q = f (A, E, L, M, K, t) $$

where $t$ represents a time trend which is assumed to capture exogenous technological change.

If we assume a production function with convex isoquants and cost minimizing aluminium

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1 At least with respect to the labour input this is a rather likely outcome given the less stringent labour laws and higher staffing levels compared to most Western European smelters.

2 The oil price shocks of the 1970s led to a major relocation of production capacity in the aluminium industry. For instance, the primary aluminium industry in Japan, once the second biggest in the world, was rapidly dismantled over little more than a decade following the oil crises (Peck et. al., 1988).

3 One may also question whether Lindquist’s results can be interpreted as true short-run responses. She uses pooled plant-level and time-series data, but (since the cross-section variance is not removed with, for instance, a fixed effects procedure) it is hard to determine whether the estimates will reflect short- or long-run (or intermediate-run) behaviour (e.g., Stapleton, 1981). Larsson (2003), on the other hand, imposes fixed effects on his factor demand model, implying that his estimates are more likely to reflect short-run responses (see also below).
producers, duality theory implies the existence of a corresponding cost function completely defining the parameters of the underlying production technology (Silberberg, 1990). Given the purpose of this paper, we are mainly interested in modelling the short-run behaviour of the aluminium smelting sector. For this reason we follow the Marshallian tradition and assume an explicit short-run (restricted) cost function in which the capital input is quasi-fixed at some level other than its equilibrium level. This gives the following variable cost function:

\[ VC = f(P_A, P_E, P_L, P_M, K, Q, t) \]  

where \( VC \) represents the smelter-specific variable production costs of primary aluminium and \( P_i \) \((i = A, E, L, \text{and} M)\) is a vector of input prices for alumina, electricity, labour and materials. \( K \) in turn denotes the level of the fixed capital stock.

Furthermore, we assume that the production function is weakly separable in the sense that the mix of electricity, labour, materials and capital is independent of the choice of alumina. This particular weak separability assumption is justified by the fact that alumina demand is largely pre-determined by chemical laws in the approximate proportion of 1.936 tons per ton of primary aluminium output (Førsund and Jansen, 1983).\(^6\) This means that for a given level of production the amount of alumina demanded is fixed. The weak separability assumption enables us to analyze a separate short-run cost function of the following form:

\[ VC = f(P_E, P_L, P_M, K, Q, t) \]  

We here assume that the input prices in [3] are exogenously determined, i.e., factor markets are assumed to be competitive. Regarding electricity prices this may appear as a strong assumption. Globally many smelters have access to electricity that is either bought under long-term contracts or is self-generated. However, for the econometric estimates to be unbiased the vital issue is the \textit{exogeneity} of electricity prices. In addition, in Western Europe and the AME-region only about a fifth of the smelters in the sample use self-generated electricity and very few smelters tie the electricity price to the price of aluminium (CRU, 2004). The assumption of exogenous input prices is thus not a too far fetched claim to make.

\(^6\) An alternative treatment of the alumina input is presented in Bye and Førsund (1990) and Gagné and Nappi (2000), in which alumina are treated as a shadow input to primary aluminium. The effect on the empirical analysis is however the same; by excluding alumina from our econometric estimations we limit the number of parameters to be estimated and gain degrees of freedom, while loosing little valuable information in the process.
Furthermore, by differentiating equation [3] logarithmically with respect to input prices and applying Shephard’s lemma we can derive the cost minimizing short-run cost share equations. The general form of the cost share functions can be written;

\[
S_i = \frac{\partial \ln VC}{\partial \ln P_i} = \frac{\partial VC}{\partial P_i} \frac{P_i}{VC} = \frac{PF_i}{VC} \quad i = E, L, M
\]

where \( S_i \) is the cost share of input \( i \), and \( F_i \) represents consumption of the \( i \)th input. To enable estimation of the share equations the cost function must be specified. In this paper we choose to follow some of the earlier studies on aluminium production (e.g. Lindquist, 1995; Gagné and Nappi, 2000; Tsekouras and Zagouras, 1998; Figuerola-Ferreti, 2005) and specify a Translog cost function for the purpose of econometric estimation. The Translog function, originally proposed by Christensen et al. (1971, 1973), permits unrestricted substitution between the different inputs and it is derived as a second-order Taylor expansion of the logarithm of an arbitrary twice differentiable cost function. In our case the Translog cost function takes the form;

\[
\ln VC = \alpha_0 + \beta_0 \ln Q + \sum_{i=1}^{3} \alpha_i P_i + \frac{1}{2} \beta_{00} (\ln Q)^2 + \frac{1}{2} \sum_{i=1}^{3} \sum_{j=1}^{3} \alpha_{ij} \ln P_i P_j
\]

\[
+ \sum_{i=1}^{3} \beta_{ii} \ln Q \ln P_i + \delta_i t + \frac{1}{2} \delta_{ii} t^2 + \delta_{ij} t \ln Q + \sum_{i=1}^{3} \delta_{ii} t \ln P_i + \frac{1}{2} \beta_{kk} (\ln K)^2
\]

\[
+ \beta_k K + \gamma_k b \ln Q \ln K + \sum_{i=1}^{3} \gamma_{kk} \ln K \ln P_i + \sum_{g=1}^{G-1} \sum_{i=1}^{3} \lambda_{gg} D_g \ln P_i
\]

where \( D_g \) denotes smelter-specific dummy variables \((g=1,\ldots,G)\) (see below for further discussion). Again we can apply Shephard’s lemma and differentiate logarithmically to derive the corresponding three cost share equations:

\[
S_i = \frac{\partial \ln VC}{\partial \ln P_i} \alpha_i + \beta_0 \ln Q + \beta_k K + \sum_{i=1}^{3} \alpha_i \ln P_i + \delta_{ii} t + \sum_{g=1}^{G-1} \lambda_{gg} D_g
\]

\( i, j = E, L, M \)
The three cost share equations in [6] take explicit account of the (beginning of the time period) level of smelter capacity measured in quantity terms. These equations form the foundation for our empirical analysis and are the equations duly estimated. For the Translog function to act as a well-behaved cost function, however, the cost shares must sum to one (1), and the cost function must be linearly homogenous of degree one in prices.\(^7\) For these reasons the following parameter restrictions are imposed on the model:

\[ \sum_{i=1}^{3} \alpha_i = 1 \]  

[7]

\[ \sum_{j=1}^{3} \alpha_j = \sum_{j=1}^{3} \beta_{ij} = \sum_{j=1}^{3} \delta_j = \sum_{i=1}^{3} \lambda_{ij} = 0 \]  

[8]

One problem with the model specification in equation [6] is that the measures of production \(Q\) and capacity \(K\) tend to move closely together, thus creating multicollinearity problems when estimating the cost share equation system. To account for this problem we assume constant returns-to-scale (CRS). Following Brown and Christensen (1981) this means that the following parameter restriction \(\beta_{ij} + \beta_{ki} = 0\) is imposed on the cost share equations, and empirically the variable \(K\) will be normalized with the produced quantity \(Q\).\(^8\)

Estimation of the cost share equations in [6] with the restrictions in [7] and [8] imposed provides us with the necessary parameters to estimate the own- and cross-price elasticities of input demand, \(e_u\) and \(e_v\). Berndt and Wood (1975), following Uzawa (1962), demonstrate that these elasticities can be expressed as:

\[ e_u = \hat{S}_i \sigma_u = \frac{\alpha_u + \hat{S}_i \hat{S}_j}{\hat{S}_i}, i \neq j \quad \text{and} \quad e_v = \hat{S}_i \sigma_v = \frac{\alpha_v + \hat{S}_i^2 - \hat{S}_j}{\hat{S}_j^2} \]  

[9]

where \(\hat{S}_i\) are the fitted cost shares for input \(i\), and \(\sigma_{ij}\) represents the Allen partial elasticity of substitution. A caveat to consider is that the own- and cross price elasticities in equation [9]

\(^7\) The latter restriction implies that total cost must increase proportionally when all input prices increases proportionally and output is held fixed. Concavity and monotonicity conditions of the cost function cannot be imposed directly on the model and are instead checked by studying the estimated parameters of the model.

\(^8\) After estimating the \(VC\) cost function in [5] and the cost share equations in [6] (as a system) a likelihood ratio test confirmed that the CRS constraint could not be rejected. In the following all results presented are based on the estimation of the cost share equations alone and with the CRS assumption imposed.
are only partial. This means that they only take account of input demand changes and substitution between variable input factors when factor prices change given the constraint that the aggregate quantity of production remains constant. A second qualification regarding these elasticities is that they are valid only for the given level of the capital stock at which they are calculated. Thus, they do not provide any information about substitution between the capital input and the other variable inputs. In essence, the elasticities should only be understood as the short run – or *ex post* – responses to relative input price changes.

As was noted above, many capital intensive process industries are characterized by limited *ex post* factor substitution possibilities. For example, Bye and Førsund (1990) and Førsund and Jansen (1983) claim that the aluminium industry uses a putty-clay technology where labour and electricity requirements are embodied in the capital equipment, i.e., the factor setup is fixed and thus determined *ex ante* at the time of the investment decision. In the empirical part of the paper we perform two tests related to the short-run price responses. First, we test whether we can reject the hypothesis of zero price effects, i.e., $\alpha_{ij} = 0$ for all $i, j$, implying the possible collapse of the Translog into a Cobb-Douglas technology.\(^9\) Second, if the factor set is fixed in the short run it implies the existence of a Leontief technology.\(^10\) In order to perform an explicit test of the zero substitutability condition, i.e., $\varepsilon_{y} = \varepsilon_{u} = 0$ (or alternatively that $\sigma_{y} = \sigma_{u} = 0$), we use the definition of the price elasticities and test whether in each period:

\[
\alpha_{y} = -\dot{S}_{j} \dot{S}_{j} \quad \text{and} \quad \alpha_{u} = \dot{S}_{i} - \dot{S}_{i}^2
\]

The restricted null hypothesis implies that price changes fully affect cost shares, and this can be tested by means of a Likelihood ratio test.

In order to test the hypothesis that smelters with more recent vintages are more flexible – and will thus be able to respond more quickly and strongly to changing input prices than older smelters – we also estimate a model introducing an interactive slope dummy

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\(^9\) Homotheticity (i.e., all input coefficients are independent of scale) in addition to the absence of price effects imply a Cobb-Douglas production technology.

\(^10\) In order to test for this hypothesis we first estimated a Generalized Leontief (GL) input-output specification originally developed by Dievert (1971) and extended by, for instance, Parks (1971) and Morrison (1988). The GL-specification, which under the restrictions $a_{ij} = 0$ for all $i, j$ collapses into a Leontief model representing a fixed coefficient technology, enabled us to test the hypothesis of no *ex-post* input substitution. However, the GL-specification generally performed badly, violating concavity and monotonicity conditions for a large number of observations, and was thus discarded since it seemingly misrepresented the underlying production technology.
variable for the input price variables and a dummy variable which equals 1 if the smelter was built after the year 1978 (and zero otherwise). Specifically, in each of the cost share equations we add the following terms:

$$\sum_{i=1}^{k} \omega_j D_i P_i$$

[11]

where $D_i$ is the 0/1 dummy variable and $\omega_j$ are the corresponding interactive coefficients.

The necessary restrictions for ensuring linear homogeneity of degree one in prices are also imposed on this extended model. With this procedure we can test the hypothesis that the partial price elasticities differ with respect to smelter vintage. The choice of 1978 as the breaking point year is mainly due to the fact that at this time five years had passed since the first OPEC oil crisis, which implied significantly higher energy prices and also led to the shutting down of the Japanese primary aluminium industry. Thus, in 1978 sufficient time should have elapsed so that the effect of increased energy costs could have been incorporated into the designs of new smelters, potentially making them more flexible in their input usage.

Finally, the estimation of the cost share equations in [6] permits us to say something about the potential biasness of technological change, i.e., whether relative input use have changed due to exogenous technological developments. Specifically, the estimated parameters $\delta_i$ in [6] indicate whether technological change has been input $i$ using or saving.

DATA AND MODEL ESTIMATION ISSUES

To enable estimation of the cost share equations in [6], we need smelter-level quantity data on output, capacity and input usage. Furthermore we also need price data for the major inputs. In this paper we employ an unbalanced panel data set provided by CRU Intl. Ltd., covering the period 1990-2003. All quantitative inputs are measured in thousands of metric tons with the exception of labour and electricity. The former is calculated as the product of the number of employees at the pot line and man-hours per year and employee, while the latter is measured.

11 The data on inputs and prices used here are derived from the Aluminium Smelter Cost Database, a proprietary database provided by CRU International Ltd. The CRU data are based on several sources such as questionnaires, interviews, plant visits, published information, industry contacts and CRUs own estimates (see CRU, 2004 for further information). Using consultancy data to make broad international comparisons might give rise to questions about the quality of the data and certainly demands caution. However, since our purpose is to evaluate substitution possibilities at the individual smelter level for selected regions worldwide, few other options remain. Furthermore, CRUs large client base within the metal industries and its long experience in undertaking the collection and systemization of plant level data cause us to judge the data reliable.
as the total electricity use in MWh at the pot line. Consequently, for electricity, input prices are measured in US$ per MWh. Since the database did not include any specific wage rate the price for labour was calculated as the ratio between total labour cost – itself the product of labour cost per ton of aluminium and smelter production – and total man-hours. The price for other materials \( M \) represents a weighted aggregate of the four inputs making up the carbon/anode category of inputs.\(^{12}\)

In order to permit a test of our hypothesis of differing own- and cross substitution elasticities across regions, we employ two sub-samples which are estimated separately. This leaves us with the following two unbalanced panel data sets of smelters;

- Western Europe, 22 smelters and a total of 282 observations; and
- Africa and the Middle East, 12 smelters and a total of 135 observations.

The estimation of the cost share equation system requires that a stochastic framework can be established. This specification must account for that variables not included in the estimation still enter the different smelters cost minimization activities. Accordingly, we append an additive disturbance term \( \varphi_{tg} \) to each cost share equation in [6], where \( t \) and \( g \) represents an index over the smelter-time observations. These error terms can be decomposed into three elements so that (e.g., Friedlander et al., 1993; Berndt et al., 1993):

\[
\varphi_{tg} = \alpha_{tg} + \mu_t + \phi_{tg}
\]

where \( \alpha_{tg} \) represent the smelter-specific error, \( \mu_t \) represents intra-equation inter-temporal effects by following a first order autoregressive processes (but no error autocorrelation cross equations). Finally, \( \phi_{tg} \) is the normally distribute error term that may be contemporaneously correlated across equations. We can interpret the smelter specific errors, \( \alpha_{tg} \), as unobserved fundamental differences across smelters (e.g., varieties of the Soderberg and/or Prebake technologies). By assuming that these dissimilarities are fixed over time, we can eliminate the disturbance term by invoking a smelter-specific dummy variable \( D_g \). For each cost share equation, the following terms are therefore added:

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\(^{12}\) We have deliberately excluded so called bath materials from the materials input \( M \) in our estimation. The reason for this is the comparatively small cost share (2-5 percent) for bath material, and that such small shares sometimes can be troublesome (in terms of violating the regulatory conditions) when applying a Translog cost function approach (e.g., Guilkey et al., 1983).
\[ \sum_{g=1}^{G-1} \gamma_{g} D_{g} \] where \( D_{g} = 1 \) for smelter \( g \) and 0 otherwise \[ [13] \]

and for theoretical consistency the term \( \sum_{g=1}^{G-1} \sum_{j=1}^{3} \lambda_{g} D_{g} \ln P_{j} \) is appended to the Translog variable cost function in [5]. The necessary cross-equation restrictions are also imposed on the fixed effect parameters. Our purpose is to estimate the short-run behaviour of smelters. The smelter dummy procedure in equation [13] is in line with these intentions since all cross-smelter variance in the cost share equations are removed and we rely solely on within-smelter variations (Baltagi, 1995). Furthermore, since cross-equation contemporaneous correlation of the \( \phi_{g} \) terms is expected we assume that the resulting disturbance vector is multivariate normally distributed with mean zero and a constant (non-singular) covariance matrix \( \Omega_{g} \).

Finally, to avoid singularity in the disturbance covariance matrix when we estimate the full system of cost share equations in [6], we drop the electricity cost share equation, thus estimating only the cost share equations for labour and materials (e.g., Greene, 1997). The electricity cost share can then be obtained by using the adding-up constraints in [7] and [8]. Since the system of equations is estimated by the method of maximum likelihood (using the TSP software) the results are invariant to the choice of equation to be dropped (Berndt, 1991).

**EMPIRICAL RESULTS**

Table 1 presents the parameter estimates of the Translog cost-share model (the base model) as well as the extended model with the vintage dummy included. Both model estimations are presented for the Western European and the Africa-Middle East (AME) cases. We will start by discussing the results from the base model and revert to the findings from the extended model later in this section. The short-run Translog specification ostensibly provides a good fit of the cost share equations in terms of conventional \( R \)-square measures. For the estimated equations the \( R \)-square measures range between 0.84 to just under 0.98. The high degree of explanation is partly due to the inclusion of smelter intercept dummies. Overall the \( t \)-statistics are satisfactory. Before proceeding, we must however stop to comment upon whether our estimated model is well-behaved or not. A cost function and the derived cost share equations are well behaved if: (a) the fitted cost shares are strictly positive, implying monotonicity of costs with respect to input prices; and (b) the model exhibits concavity in input prices (Chambers, 1988). In our estimations, all cost shares, regardless of region and model, were
found to be positive. We then examined whether the bordered Hessian matrix is negative semi-definite, which is both a necessary and a sufficient condition for concavity. The check itself is performed by examining the signs of the principle minors at each observation. Apart from 30 observations (out of 282) for Western Europe and 16 (out of 135) for the AME-region, the Translog cost share models were well-behaved. In sum, in spite of some concavity violations in our estimations, our models appear reasonably consistent with its theoretical restrictions.

Table 1. Parameter Estimates for the Translog Cost Share Systems

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Western Europe</th>
<th>Africa &amp; the Middle East</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Base-estimation</td>
<td>Age-dummy</td>
</tr>
<tr>
<td></td>
<td>Estimate</td>
<td>t-statistics</td>
</tr>
<tr>
<td>$\alpha_L$</td>
<td>21DV$^1$</td>
<td>21DV$^1$</td>
</tr>
<tr>
<td>$\alpha_M$</td>
<td>21DV$^1$</td>
<td>21DV$^1$</td>
</tr>
<tr>
<td>$\alpha_E$</td>
<td>21DV$^1$</td>
<td>21DV$^1$</td>
</tr>
<tr>
<td>$\alpha_{LL}$</td>
<td>0.199</td>
<td>***18.19</td>
</tr>
<tr>
<td>$\alpha_{LM}$</td>
<td>-0.048</td>
<td>***8.97</td>
</tr>
<tr>
<td>$\alpha_{LE}$</td>
<td>-0.151</td>
<td>***-18.55</td>
</tr>
<tr>
<td>$\alpha_{MM}$</td>
<td>0.133</td>
<td>***31.51</td>
</tr>
<tr>
<td>$\alpha_{ME}$</td>
<td>-0.085</td>
<td>***-20.64</td>
</tr>
<tr>
<td>$\beta_{LEKQ}$</td>
<td>0.015</td>
<td>**2.21</td>
</tr>
<tr>
<td>$\beta_{MKQ}$</td>
<td>-0.076</td>
<td>**2.14</td>
</tr>
<tr>
<td>$\beta_{EKQ}$</td>
<td>-0.070</td>
<td>-1.38</td>
</tr>
<tr>
<td>$\delta_{LL}$</td>
<td>-0.031</td>
<td>***-8.84</td>
</tr>
<tr>
<td>$\delta_{MM}$</td>
<td>0.021</td>
<td>***10.30</td>
</tr>
<tr>
<td>$\delta_{EE}$</td>
<td>0.0094</td>
<td>***3.38</td>
</tr>
<tr>
<td>$\omega_{LL}$</td>
<td>0.076</td>
<td>**2.21</td>
</tr>
<tr>
<td>$\omega_{LM}$</td>
<td>-0.019</td>
<td>-1.42</td>
</tr>
<tr>
<td>$\omega_{LE}$</td>
<td>-0.056</td>
<td>**-2.08</td>
</tr>
<tr>
<td>$\omega_{MM}$</td>
<td>0.019</td>
<td>**2.14</td>
</tr>
<tr>
<td>$\omega_{ME}$</td>
<td>0.011</td>
<td>0.11</td>
</tr>
<tr>
<td>$\omega_{EE}$</td>
<td>0.055</td>
<td>**2.27</td>
</tr>
</tbody>
</table>

Log-likelihood | 1630.59 | 1635.43 | 726.92 | 744.96 |

$N$ | 282 | 282 | 135 | 135 |

$^1$ DV$^1$ indicates the use of separate dummy intercept variables for each mill. Specifically, in the cost share equations in [6] there is a value $\alpha_i$ for a base smelter and then an additional $\lambda_{ig}$ for the remaining G-1 smelters. The full set of parameter estimates is available from the authors upon request.

*, **, *** Statistical significance at the ten, five and one percent levels, using a two tailed test.
As was noted above, our focus is on the possible presence of *ex post* factor substitution, and for this reason we test the two null hypotheses that (a) the cost shares are independent of fuel prices (i.e., $\alpha_{ij} = 0$ for all $i, j$), and (b) the elasticities of substitution between all input factors are all zero (i.e., implying from the above that $\alpha_{ij} = -\hat{S}_i \hat{S}_j$ and $\alpha_{ii} = \hat{S}_i - \hat{S}_i^2$). The restricted versions of the models are tested against the less restricted ones by means of a likelihood ratio (LR) test. The appropriate test statistic is computed as $-2(\ln LL_{RR} - \ln LL_{UR})$, where $L$ is the likelihood value (calculated from the residual covariance matrix). $RR$ denotes the restricted model and $UR$ the restricted one. The LR statistic is distributed asymptotically as a chi-square ($\chi^2$) random variable with degrees of freedom equal to the number of restrictions being tested (Berndt, 1991). The results from the LR tests are displayed in Tables 2 and 3, and they indicate strong rejections of the null hypotheses of zero price effects and zero factor substitutability. Thus, the empirical evidence supports the notion that short-run price induced factor substitution should not be neglected in economic analyses of the aluminium smelting sector. Accordingly, we now investigate the observed cross-price effects in more detail. Assessment of these is however carried out more readily using the estimated partial price elasticities.

**Table 2. Likelihood Ratio Test for Zero Price Effects**

<table>
<thead>
<tr>
<th>Region</th>
<th>Null Hypothesis</th>
<th>Test statistic for LR-test</th>
<th>Critical Value $\chi^2 (0.01)$</th>
<th>Critical Value $\chi^2 (0.005)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Western Europe</td>
<td>$\alpha_{LM} = \alpha_{LE} = \alpha_{EM} = 0$</td>
<td>758.82</td>
<td>11.34</td>
<td>12.84</td>
</tr>
<tr>
<td>Africa-Middle East</td>
<td>$\alpha_{LM} = \alpha_{LE} = \alpha_{EM} = 0$</td>
<td>415.44</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 3. Likelihood Ratio Test for Zero Factor Substitutability**

<table>
<thead>
<tr>
<th>Region</th>
<th>Null Hypothesis</th>
<th>Test statistic for LR-test</th>
<th>Critical Value $\chi^2 (0.01)$</th>
<th>Critical Value $\chi^2 (0.005)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Western Europe</td>
<td>$\alpha_{ij} = -\hat{S}_i \hat{S}<em>j$, $\alpha</em>{ii} = \hat{S}_i - \hat{S}_i^2$</td>
<td>236.00</td>
<td>12.59</td>
<td>16.81</td>
</tr>
<tr>
<td>Africa-Middle East</td>
<td>$\alpha_{ij} = -\hat{S}_i \hat{S}<em>j$, $\alpha</em>{ii} = \hat{S}_i - \hat{S}_i^2$</td>
<td>101.29</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The short-run own- and cross-price elasticities of demand resulting from the estimation of our base model for the two regions are presented in Table 4. The elasticities have been calculated at the mean value of the fitted cost shares over the time period 1990-
2003. We would expect the own-price elasticities of demand to be non-positive, and this is true for all estimates with the exception of labour demand in Western Europe (reflecting the failure of the underlying cost function to be concave in factor prices). This latter result may in part reflect the fact that in Western Europe labour essentially is a fixed factor in the short-run (while its use probably can be more easily adjusted in the AME-region). In order to test the robustness of our results for Western Europe we therefore also tested a model in which labour is treated as fixed, i.e., labour is accounted for but changes in labour demand are not explained. Appendix A presents the results from this alternative estimation, and it shows that when labour is treated as a quasi-fixed variable the own-price elasticities (for the materials and energy inputs) increase slightly but they are still generally low. Furthermore, material demand remains more own-price elastic than energy demand.

Table 4. Estimated Partial Own- and Cross-Price Elasticities of Input Demand

<table>
<thead>
<tr>
<th>Own-price</th>
<th>Western Europe</th>
<th>Africa &amp; the Middle East</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_{LL}$</td>
<td>0.008</td>
<td>-0.381</td>
</tr>
<tr>
<td>$\varepsilon_{MM}$</td>
<td>-0.144</td>
<td>-0.124</td>
</tr>
<tr>
<td>$\varepsilon_{EE}$</td>
<td>-0.027</td>
<td>-0.074</td>
</tr>
<tr>
<td>Cross-price</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\varepsilon_{LM}$</td>
<td>0.024</td>
<td>0.145</td>
</tr>
<tr>
<td>$\varepsilon_{ML}$</td>
<td>0.032</td>
<td>0.089</td>
</tr>
<tr>
<td>$\varepsilon_{LE}$</td>
<td>-0.032</td>
<td>0.236</td>
</tr>
<tr>
<td>$\varepsilon_{EL}$</td>
<td>-0.017</td>
<td>0.060</td>
</tr>
<tr>
<td>$\varepsilon_{EM}$</td>
<td>0.043</td>
<td>0.014</td>
</tr>
<tr>
<td>$\varepsilon_{ME}$</td>
<td>0.112</td>
<td>0.035</td>
</tr>
</tbody>
</table>

Overall the results in Table 4 signal inelastic responses to changes in own prices, something which is in line with our a priori notion of limited (although not insignificant) ex post substitution possibilities in primary aluminium smelting. Smelters in the AME-region seem – with the exception of material demand – to be generally more sensitive to short-run price changes than their counterparts in Western Europe. For instance, a 10 percent wage increase would reduce labour demand in the AME-region by almost 4 percent for a given level of output. Such a strong short-run response likely reflects the presence of less stringent labour laws and higher staffing levels compared to Western European smelters. If we consider
the own-price elasticities for electricity, smelters in the AME-region appear again more flexible in their response, although both regions display rather limited responses.

The estimated cross-price elasticities confirm the overall picture of limited ex post factor substitution. Furthermore, the cross-price elasticities are generally higher for smelters in the AME-region than for the Western European sample. Again, the only exception to this concerns the substitution between electricity and material. While there is almost no substitution between labour and materials in Western Europe, AME-smelters display relatively high price responses. In addition, in the AME region electricity and labour are substitutes and the reported cross-price elasticities are non-negligible, while in Western Europe these two input factors come out as complements but with low absolute values. The rigidity of the Western European labour markets should play a role in explaining this overall pattern. A partial explanation to the reported higher price responses in the AME-region is however also the greater number of pot lines with slightly different technologies at each smelter. Changes in factor prices can – in the absence of full capacity utilization – alter the order in which different pot lines are brought on-line. From the CRU data we know that in Western Europe the number of pot lines in our sample never exceeds 3 for any of the smelters, while in the AME-region the average number of pot lines equals 3.5. Figure 2 shows the development of capacity utilization in the respective regions over the time period 1990-2003.

![Figure 2: Capacity Utilization Rates for Aluminium Smelting Plants, 1990-2003](image)

---

13 A smelter technically consists of one or several so-called pot lines, each consisting of a number of reduction cells or pots, connected in series to a source of direct electrical power. Different pot lines can be assumed to be brought on-line according to their short-run variable costs of production.
Figure 2 displays that both regions have experienced extended periods with less than full capacity utilization, and our results are consistent with the notion that the AME-region in particular has been able to make some use of this situation and substitute between inputs based on annual relative price changes.

When comparing our own-price demand elasticities with the ones found in the two studies by Lindquist (1995) and Larsson (2003) of the Norwegian primary aluminium industry similar responses are found (see Table 5). Exceptions include the elasticities for electricity, which are notably lower in our study. One possible explanation for this is that the Norwegian studies are valid only for one country and cover earlier time periods.\textsuperscript{14} It is possible that it has become increasingly harder to make further decreases in relative electricity use over the years as the industry approaches the theoretical minimum required to drive the electrolytic process using the Hall-Heroult process (King, 2001; Das et. al., 2004). Our estimated cross-price elasticities in Table 4 indicate that with the exception of labour and electricity in Western European smelters, all inputs are substitutes. Compared with the two studies above, there seems to be only limited agreement whether inputs are to be classified as substitutes or complements in the smelting process. Only when it comes to the case of labour demand responses caused by changes in materials prices all three studies concur. However, part of these differences might be explained by the different definitions of the materials input used. Both Lindquist and Larsson use a much broader definition, including alumina in the materials category. We explicitly exclude alumina from our estimations treating it as shadow input to output. Thus, in the studies by Lindquist and Larsson, respectively, electricity and materials are complements in production while we find them to be (weak) substitutes.


<table>
<thead>
<tr>
<th></th>
<th>Labour/ $P_L$</th>
<th>Mtrls/ $P_M$</th>
<th>Electr./ $P_E$</th>
<th>Labour/ $P_L$</th>
<th>Mtrls/ $P_M$</th>
<th>Electr./ $P_E$</th>
<th>Labour/ $P_L$</th>
<th>Mtrls/ $P_M$</th>
<th>Electr./ $P_E$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lindquist*</td>
<td>-0.48</td>
<td>-0.11</td>
<td>-0.22</td>
<td>0.30</td>
<td>0.12</td>
<td>-0.02</td>
<td>-0.01</td>
<td>0.18</td>
<td>0.24</td>
</tr>
<tr>
<td>Larsson**</td>
<td>-0.44</td>
<td>-0.21</td>
<td>-0.23</td>
<td>0.04</td>
<td>-0.06</td>
<td>-0.09</td>
<td>0.06</td>
<td>0.08</td>
<td>0.06</td>
</tr>
<tr>
<td>This study: WE</td>
<td>0.008</td>
<td>-0.144</td>
<td>-0.027</td>
<td>0.024</td>
<td>0.032</td>
<td>0.043</td>
<td>0.112</td>
<td>-0.032</td>
<td>-0.017</td>
</tr>
<tr>
<td>This study: AME</td>
<td>-0.381</td>
<td>-0.124</td>
<td>-0.074</td>
<td>0.145</td>
<td>0.236</td>
<td>0.014</td>
<td>0.035</td>
<td>0.236</td>
<td>0.060</td>
</tr>
</tbody>
</table>

* Estimates are for the AR-model. ** Figures are for the one good (output) model. Larsson also includes fuel as an input, but these elasticities are not reported here.
Sources: Table 3.7 in Lindquist (1995), Table 4.4 in Larsson (2003) and Table 4 in the present study.

The results from the inclusion of vintage slope-dummy variables in our cost share models are displayed in Table 1. We find here that a few of these dummies are statistically significant (at the five percent level or lower). Table 6 presents the resulting partial price elasticities for the two different age classes.

Table 6. Estimated Partial Own- and Cross-Price Elasticities of Input Demand for Smelters Constructed Pre- and Post 1978

<table>
<thead>
<tr>
<th>Own-price</th>
<th>Western Europe</th>
<th>Africa &amp; the Middle East</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre-1978</td>
<td>Post-1978</td>
</tr>
<tr>
<td>$E_{LL}$</td>
<td>-0.025</td>
<td>0.257</td>
</tr>
<tr>
<td>$E_{MM}$</td>
<td>-0.164</td>
<td>-0.074</td>
</tr>
<tr>
<td>$E_{EE}$</td>
<td>-0.037</td>
<td>0.068</td>
</tr>
<tr>
<td>Cross-price</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E_{LM}$</td>
<td>0.039</td>
<td>-0.034</td>
</tr>
<tr>
<td>$E_{ML}$</td>
<td>0.051</td>
<td>-0.045</td>
</tr>
<tr>
<td>$E_{LE}$</td>
<td>-0.014</td>
<td>-0.223</td>
</tr>
<tr>
<td>$E_{EL}$</td>
<td>-0.007</td>
<td>-0.114</td>
</tr>
<tr>
<td>$E_{EM}$</td>
<td>0.044</td>
<td>0.046</td>
</tr>
<tr>
<td>$E_{ME}$</td>
<td>0.113</td>
<td>0.119</td>
</tr>
</tbody>
</table>

For Western Europe first there is a tendency that the short-run substitution possibilities are reduced over time, and this is most evident for labour and material. These two factor inputs even move from being substitutes to complements. We do not thus find any evidence in support of our hypothesis that Western Europe – a region in decline – has responded to the competition from the new regions by increasing its ability to respond to short-run price changes. In fact a LR test of the restricted base model against the more flexible model including vintage slope dummies indicates that the null hypothesis that the overall impact of these dummies was statistically insignificant could not be rejected.15 In the AME-region on the other hand the experiences are more or less the opposite. The LR test here shows that there is a statistically significant difference between the two models.16 Both labour and material demands become more own-price elastic over time, and these inputs become even stronger substitutes. However, as in the Western Europe case the own-price elasticity of electricity demand become lower, and the ex post possibilities to switch between electricity and other

15 The LR statistic equals 9.68 and the critical value at the five percent significance level (with three degrees of freedom) is 12.84. Since the coefficients $o_i$ for a given $i$ sum to zero only three coefficients are independent. Thus, effectively we only test for three restrictions.

16 In this case the LR statistic equals 36.08.
factor inputs are reduced when moving from old to new vintages. Thus, our hypothesis that smelters built after the first oil crises are more flexible in their electricity use (compared to pre-crisis smelters) gains no support for either of the regions.

Finally, the estimates for the time trend coefficients show that the null hypothesis of Hicks neutral technical change can be strongly rejected, but we also find interesting differences across regions. First, in Western Europe technical change has been labour saving, while the estimated trend coefficient for labour in the AME-region is not statistically significant. In part these differing results reflect varying policies across smelters in the two regions. Smelters in the AME-region are often state-owned, and to some extent their existence is motivated not only by making use of abundant energy sources but also by regional development and industrial diversification objectives. In addition, labour is relatively costly in Western Europe compared to the AME-region, putting a premium on technical progresses that can enhance labour productivity in the former region. Second, the time trend coefficient for electricity displays that technical change has been electricity using in Western European smelters. Electricity savings occur mainly when smelters are significantly modernized and/or in the case of Greenfield investment. Hence, the lack of relative electricity savings in Western Europe can partly be explained by the lower frequency of investment in this region compared to the AME-region. According to the CRU database (CRU, 2004), just over one fifth of the smelters in the Western European sample underwent major modifications during the period 1990-2003, of which only one was constructed completely from scratch. This compares with over two fifths significantly remodelled in the AME-region, whereof two fully new smelters being constructed over the period. Third and finally, in both regions exogenous technical change has had a positive and statistically significant bias on material usage.

CONCLUDING DISCUSSION
Short-run factor demand flexibility may become an important survival strategy for selected process industries, not the least since some factor input markets (in particular electricity) are

17 Apart from some minor plants in China all new smelters built over the last few decades typically use varieties of the Prebake technology, and existing smelters are continuously being upgraded, switching from the Soderberg continuous process to Prebake technology. According to Bergsdal et al. (2004) an average Soderberg smelter consumes 16.6 MWh of electricity per ton aluminium produced compared to 13.3 MWh for the most modern Prebake smelters. In addition, primary smelters are either built or upgraded with larger and more efficient cells operating under higher amperages, thus also reducing electricity consumption (King, 2001).

18 It is likely that this overstates the number of modernized smelters in Western Europe since the share reported here is valid only for smelters active in 2003. For smelters decommissioned during the period we do not have data on start-up and modernization year. These smelters are less likely to have undergone any significant modernisations.
likely to become more volatile in the future as a result of market liberalizations and new environmental policy instruments (such as emissions trading). This paper has estimated the degree of *ex post* factor demand flexibility in the primary aluminium industry in Western Europe and the AME region. The empirical results suggest that the null hypothesis of zero *ex post* factor substitutability can be rejected. Still, overall the short-run own- and cross-price elasticities of factor demand are (as anticipated) low.

Aluminium smelters in the AME region show evidence of higher short-run own- and cross-price elasticities than their competitors in Western Europe, at least when it comes to labour and electricity demand. For instance, while there is almost no substitution between labour and materials in Western Europe, AME-smelters display relatively high price responses. The high price sensitivity in the latter region likely reflects the presence of less stringent labour laws and higher staffing levels compared to Western European smelters. A partial explanation to the reported higher price responses in the AME-region is however also the greater number of pot lines with slightly different technologies at each smelter. Western European smelters can however more easily switch between the material input and electricity.

The empirical results also suggest that in both regions the demand for electricity has over time become less sensitive to short-run price changes. Thus, our hypothesis stating that smelters built after the first oil crises are more flexible in their electricity use (compared to smelters of older vintages) gains no support for either of the regions. However, in the AME region both labour and material demands have become more own-price elastic over time, and these inputs are stronger substitutes in new smelters compared to smelters of earlier vintages.

The liberalization of the electricity markets in combination with the rigid labour markets in Western Europe suggest that the shift in production capacity from the western world to the AME-region as well as China may well continue. Although technical change has led to substantial labour input savings in the Western European aluminium industry, the cost disadvantages are still there, and the European smelters are less capable of responding to short-term price movements when compared to its competitors in Africa and the Middle East.

**REFERENCES**


APPENDIX A: Translog Cost-share Model with Labour as a Quasi-fixed Input

Table A1. Parameter Estimates for Cost Share Model for Western Europe with Labour as a Fixed Factor

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Western Europe</th>
<th>Estimate</th>
<th>t-statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_M$</td>
<td>= 2</td>
<td>$21D^1*$</td>
<td></td>
</tr>
<tr>
<td>$\alpha_E$</td>
<td>= 2</td>
<td>$21D^1*$</td>
<td></td>
</tr>
<tr>
<td>$\alpha_{MM}$</td>
<td>= 0.120</td>
<td>***26.00</td>
<td></td>
</tr>
<tr>
<td>$\alpha_{ME}$</td>
<td>= -0.120</td>
<td>***-26.00</td>
<td></td>
</tr>
<tr>
<td>$\alpha_{EE}$</td>
<td>= 0.120</td>
<td>***26.00</td>
<td></td>
</tr>
<tr>
<td>$\beta_{MKQ}$</td>
<td>= -0.012</td>
<td>*-1.86</td>
<td></td>
</tr>
<tr>
<td>$\beta_{EKQ}$</td>
<td>= 0.012</td>
<td>*1.86</td>
<td></td>
</tr>
<tr>
<td>$\delta_M$</td>
<td>= 0.002</td>
<td>***8.57</td>
<td></td>
</tr>
<tr>
<td>$\delta_D$</td>
<td>= -0.002</td>
<td>***-8.57</td>
<td></td>
</tr>
<tr>
<td>$\phi_{ML}$</td>
<td>= -0.0015</td>
<td>-0.26</td>
<td></td>
</tr>
<tr>
<td>$\phi_{EL}$</td>
<td>= 0.0015</td>
<td>0.26</td>
<td></td>
</tr>
</tbody>
</table>

Log-likelihood 838.293
N 282

$DV$ indicates the use of separate dummy intercept variables for each mill. Specifically, in the cost share equations [6] there is a value for $\alpha$, for a base smelter and then an additional $\lambda_g$ for the other $G-1$ smelters. The full set of parameter estimates is available from the authors upon request.

*, **, *** Denote statistical significance at the ten, five and one percent levels, using a two tailed test.

Table A2. Estimated Partial Own- and Cross-Price Elasticities of Input Demand with Labour as a Fixed Factor

<table>
<thead>
<tr>
<th>Western Europe</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Own-price</strong></td>
</tr>
<tr>
<td>$\varepsilon_{MM}$</td>
</tr>
<tr>
<td>$\varepsilon_{EE}$</td>
</tr>
<tr>
<td><strong>Cross-price</strong></td>
</tr>
<tr>
<td>$\varepsilon_{EM}$</td>
</tr>
<tr>
<td>$\varepsilon_{ME}$</td>
</tr>
</tbody>
</table>
Short-run demand and supply elasticities in the West European market for secondary aluminium

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Abstract

As the principal user of old scrap, secondary aluminium smelters and refiners have traditionally played a key role in the recycling of aluminium, producing primarily cast material demanded primarily by the automobile industry. The purpose of this paper is to explore the supply–demand relationships in the market for secondary aluminium alloys. Based on a standard microeconomic model, where the determinants of supply and demand are identified, an econometric model, using data from Germany, France, Italy and the UK for the time period 1983–97, is estimated. The model is used to assess the relative importance of the factors determining the supply and demand of the European secondary aluminium industry. The results show that both the supply and the derived demand for secondary aluminium is own-price inelastic, which is reasonable given the short-run framework. On the demand side, the level of auto production is found to have a substantial impact on the level of secondary aluminium alloy demand. We conclude that the model describes the market reasonably well. The inelastic supply in combination with the sensitivity to changes in the level of auto production provides a tentative explanation of the observed volatility in secondary aluminium prices. Furthermore, the inelastic supply responses indicate that policies aimed at increasing recycling using price-based incentives will be inefficient.

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Keywords: Secondary aluminium; Aluminium recycling; Panel data; Supply and demand; West Europe

Introduction

Purpose and background

Recycling is sometimes viewed as an activity guided by forces other than those prevalent in the market. Hence there is a perception that recovery of worn-out products and the production of new material from these need to be mandated or otherwise regulated. However, markets for recycled metal scrap and the products derived from it have existed for a considerable time. The purpose of this paper is to explore the supply–demand relationships in the West European market for secondary aluminium casting alloys.1 Building on a standard microeconomic model of short-run price determination we will identify and estimate the determinants of supply and demand. This effort is not only interesting because it adds to our understanding of an important recycling market, it will also help us to understand the high volatility in secondary aluminium prices. For example, the German secondary aluminium alloy price reached a high of 70 ct/lb in

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1 By secondary aluminium we mean metal predominantly produced from aluminium scrap. It should be noted that with this market definition, we leave out a great portion of the aluminium recycling industry. The remelter industry, for example, recycles considerable amounts of new (production) scrap. Our motivation for not including supply from remelters is that many of them work on a toll basis or are integrated with primary smelters. Thus, their supply is not determined by market forces to the same extent as the secondary refinery industry supply is. A further motivation is that we want to capture the market forces driving the recovery of scrap from worn-out products (old scrap). For technical reasons, the refinery industry is the only part of the aluminium industry that is able to use old scrap. See Results and Analysis in this paper for further details.
Table 1
Production and consumption of aluminium in Europe in 1970–97 (thousand tons)

<table>
<thead>
<tr>
<th>Year</th>
<th>Production of secondary aluminium</th>
<th>Production of primary aluminium</th>
<th>Total consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>1970</td>
<td>800.5</td>
<td>2015.1</td>
<td>3347.8</td>
</tr>
<tr>
<td>1980</td>
<td>1183.5</td>
<td>3759</td>
<td>5048.6</td>
</tr>
<tr>
<td>1990</td>
<td>1712.1</td>
<td>3927.4</td>
<td>6907.3</td>
</tr>
<tr>
<td>1997</td>
<td>1851.4</td>
<td>3299.5</td>
<td>7900.2*</td>
</tr>
</tbody>
</table>

Source: Metal Statistics and Organisation of European Aluminium Refiners and Remelters (OEA).

* 1995.

real terms both in 1984 and 1989 and a low of 30 ct/lb in 1994. Such swings in price might have detrimental effects on the willingness to undertake long-term investment in the industry, with possible negative ramifications for recycling.

Recycling of aluminium has been undertaken since the metal started to be used in the late-nineteenth century, primarily due to the high value of the scrap because of the energy-saving potential when manufacturing metal from aluminium scrap instead of bauxite. However, only in the 1980s and 1990s has aluminium recycling entered the public consciousness. Today, municipal recycling centers for used beverage cans are more or less common throughout the western world, as is the recycling of almost all aluminium metal from end-of-life vehicles. Aluminium is the world’s most used non-ferrous metal, with annual world consumption twice as high as copper (aluminium is second only to iron and steel). Its prominent role in public discussion is not misplaced. In Western Europe, recycling of aluminium scrap and the production of secondary metal from it has taken on even more prominence since European primary production started to level off and finally decline during the 1980s and 1990s. As is evident from Table 1, the relative growth of the secondary refinery industry has been almost one and a half times as rapid as the growth in the primary sector, partly due to the high energy cost of the latter. Table 2 indicates the great importance of the secondary refinery industry for some major European countries. The relative size of the two industries has varied over the last 30 years, but since the beginning of the 1980s the secondary industry has grown consistently in importance and is now, in the case of Italy, more than twice the size of the primary industry. Even if total consumption of aluminium over time has often outgrown any domestic supply in most European countries, secondary aluminium has held its position reasonably well. In 1997, secondary aluminium comprised approximately one-fifth to almost one-third of total consumption.

Given the growing importance of secondary aluminium both in terms of European “domestic” production and in terms of the growing share of consumption, we believe there is a need to better understand how the market for secondary alloys functions.

Earlier research

Owing to this demonstrated significant role of secondary aluminium, it is surprising that it has hitherto attracted so little attention from academia. Many of the earlier studies of metal recycling, such as Bonzcar and Tilton (1975), Slade (1980) and Stollery (1983), concentrate on the recycling of copper in the USA. Only very few efforts have been made to study other metals (such as aluminium) and other countries or regions.

One example of such an effort is a study by Grace (1978). Grace attempts to establish a method to calculate recycling rates for metals and uses it to compare recycling rates between countries. While using aluminium as the base case, he also applies the method to copper and lead. He calculates recycling rates for the three metals for six countries—Germany, France, Italy, the UK, the USA and Japan—during the period 1965–75. He concludes that there seems to be evidence that the supply of scrap aluminium outgrows the demand for castings made from secondary aluminium. Hence, increased...
recycling must come either from increased use of castings or from technological development allowing secondary aluminium to be used in wrought products as well. While not formally evaluating what causes the differences in recycling ratios between countries, Grace tentatively suggests that it could be explained by differences in the growth of consumption, different end-use structure of aluminium and, finally, by differences in factor endowments, with emphasis on the domestic availability of bauxite.

Carlsen (1980) attempts to explain changes in the recycling rate of aluminium in the USA during the period 1954–76. The recycling ratio, defined as the share of recovered aluminium scrap out of total aluminium consumption, is explained by three factors: the cost of energy, aluminium scrap price relative to primary price, and the level of industrial production. The ordinary least square (OLS) results indicate that higher energy prices increase the recycling effort by making the energy-intensive primary production relatively more costly. The higher relative price of scrap makes recovery and recycling more profitable and, hence, is linked with higher recycling ratios. Finally, increases in industrial activity also lead to increased recycling of aluminium. Carlsen’s results also show that the main part of the responsiveness of the recycling ratio comes from new (industrial) scrap.

Westenbarger et al. (1991) calculate welfare gains due to energy savings if secondary aluminium production in the US increased. They use a translog cost function, using data for 1965–87 to arrive at the derived demand for inputs for the US aluminium industry. The aluminium industry is treated as a whole, i.e. no difference between primary producers and secondary refiners is made, although the authors acknowledge the different quality requirements of cast and wrought production. They conclude that substitution of 5 percent of the bauxite used for aluminium scrap would lead to savings of about a quarter of a billion dollars.

All three studies above, treating aluminium recycling, are in one way or another preoccupied with the recycling ratio. This is of course all fine, but in all three there seems to be some neglect of how the market for secondary aluminium alloys really works. For example, the studies by Grace and Carlsen, apart from being slightly outdated, treat aluminium recycling as a “unified” process with one market, when it is, in fact, at least two divided stages, i.e. recovery stage performed by scrap collectors, etc., and the recycling stage where refiners are active. Each of these stages represents different markets with its own distinguishing features and determinants. In the Westenbarger et al. case, they have a different motive for their effort, and recycling is only discussed indirectly. What is important, however, is that they implicitly assume that primary and secondary aluminium are near-perfect substitutes, competing in the same market, which they are not. Secondary aluminium dominates in castings and can only, to a very limited extent, be substituted for primary in wrought semi-production. To summarize, most earlier efforts are lacking in one or more of the following respects; they are slightly outdated, they treat other metals, they apply mainly to the US, and finally, some of them lack in method. Clearly, there seems to be a void to fill.

Contrary to these earlier efforts, this paper will focus not on estimating recycling ratios per se, but on the market for secondary aluminium alloys (which is produced from aluminium scrap). Hence, we will focus our effort on what determines the supply of aluminium alloys produced by the secondary refinery industry. The secondary alloys are demanded by foundries to make castings, mainly for the automobile industry. The refinery industry is important because it has traditionally been the nucleus of the recycling flow (the box marked by bold lines in Fig. 1). The refinery industry processes the bulk of the aluminium scrap from end-of-life products (old scrap) and is also a major user of industrial scrap (new scrap), even though, during the last 15 to 20 years, it has faced increasing competition for new scrap from the so-called remelt industry. To concentrate on this specific market and its determinants, and not instead concentrate on what makes people turn in their automobiles and used beverage cans for recovery, is motivated by what we believe to be an insufficient understanding of how this intermediate market works. Policies aimed at stimulating recovery might turn out to be inefficient, due to factors unknown to the regulators during the later stages in processing the recovered aluminium. It could be argued, as Grace (1978) does, that one way to increase recycling of aluminium is if secondary aluminium gets a larger slice of the castings market or if aluminium castings themselves get deeper market penetration. But this raises, among other questions, the question of what guides the demand for secondary aluminium in castings.

The rest of the paper is outlined as follows: in the rest of the first part, the flow of aluminium metal will be described briefly and some necessary definitions will be introduced. In the second part, the specific factors determining supply and demand of secondary aluminium alloys are identified and examined. Also, a model for short-run price determination in a competitive market is presented along with the econometric specification and a discussion of the data used. In the third part, the results are presented and discussed. Finally, in the fourth part conclusions are drawn, some policy issues are discussed briefly, and some indications for further research are outlined.

The flow of aluminium

As Fig. 1 depicts, there are two basic sources of raw material for producing aluminium metal—bauxite and scrap. First, aluminium can be produced from mined
material, i.e. bauxite, refined first into alumina and then through the Hall–Herault process further upgraded into primary aluminium metal. Second, as an alternative source of raw material, aluminium metal can be made from scrap metal, resulting in secondary aluminium. This study is principally concerned with the latter route, or the part of the flow diagram with bold arrows.

Aluminium scrap is not, however, a homogenous material. Its quality and quantity can vary greatly. Aluminium scrap can, as in Fig. 1, be divided into two main types, depending on where it arises in the flow. New scrap (or prompt, process or production scrap) arises and is recovered during all stages in the manufacturing chain, from original smelting and refining through semi-production to the production of final goods—regardless of whether the products are made from primary or scrap metal. Examples are clippings, borings and trimmings or the skeleton remaining after can lids are stamped out of aluminium sheets. Hence, the volume of new scrap is closely linked to the level of manufacturing of aluminium-containing end-use products. The technology involved in the different manufacturing stages also plays an important role in deciding the volume of new scrap. Close to all new scrap is recovered and recycled, due to its usually known metallic composition and, hence, high value and costs of storage and deposition.

The other scrap source, depicted in Fig. 1, so-called old scrap (or obsolete, capital or country scrap) is recovered from end-use products, such as automobiles, window-frames, used beverage cans (UBCs), etc., reaching the end of their useful life. The aluminium content in all previously manufactured end-use products makes up the pool of potentially recoverable material. Usually, the material compositions of end-use products are more complex and less known than for new scrap. For example, aluminium UBCs contain two different alloys, one for the lid and one for the body of the UBC, hence demanding different types of treatment. Old scrap, therefore, demands a more rigorous treatment than that of new scrap before a secondary refiner uses it. This service is usually performed in the stage preceding refining in the recovery industry, i.e. a large number of scrap collectors and merchants that sort and upgrade the scrap according to metal content and quality, package it into “bundles” and finally market it.

The next phase, following collection and pretreatment, is smelting and refining. Secondary refiners (the box marked by bold lines in the figure) are unique in the sense that they can smelt and refine scrap of various qualities, i.e. both new and old scrap, contrary to primary producers and remelters who require purer raw material inputs. Secondary refiners, in particular, compete with remelters for new scrap of high quality (remelters produce wrought products, thus they have higher demands on the scrap material they use than secondary refiners). Owing to the mixed quality of most post-consumer scrap, secondary refiners, however, remain the prime buyers of old scrap. Secondary refiners also use limited quantities of primary aluminium as “sweeteners” to achieve the required alloy composition.

The product of secondary refiners—secondary aluminium alloys—comes in either ingot or molten form and is suitable mainly for casting products and steel deoxidants. Cast alloys are by far the most important of these products. The ingot or molten metal is then sold to foundries that produce a variety of cast products from the ingot, mainly to be used in the automotive industry. Other important sectors include, for example, general and electrical engineering and building and construction.

\footnote{One type of new scrap, not mentioned above, is so-called home scrap (or run-around, revert or in-process scrap). It arises during smelting or refining of both primary and scrap aluminium. Home scrap never enters the market, but is recycled within the production facility where it originated. Hence, it is of little interest for this study.}
The secondary aluminium market

The supply and demand for secondary aluminium alloys

Some general features of the secondary aluminium alloy market

Before outlining our model, we will examine the supply–demand relationship in the West European secondary aluminium market in more detail. Determinants of supply and demand will be identified and discussed. However, we will start by examining some general features of the secondary aluminium alloy market.

Throughout this work, we will regard the secondary alloy market as competitive. The de facto large number of secondary refiners and foundries in Western Europe makes this a workable assumption. In 1998, there were more than 200 refiners in operation throughout Europe (OEA, 1998). One explanation for the large number of secondary refiners, compared to primary producers, is that the technology used in the secondary industry involves fewer steps than in the primary industry. Thus it is cheaper. In the secondary industry, scrap metal is readily converted into secondary alloys, whereas in the primary industry we have to first convert bauxite into alumina and then, in a subsequent stage through the Hall–Herault process, refine it into aluminium metal. Another factor lowering the barriers to entry into the secondary industry is its relatively low energy demand compared to the primary aluminium industry. Primary production is very energy-intensive and thus tends to be located where cheap energy is available—which in practice means where electricity is generated by hydro power or where the industry could extract subsidized electricity rates (Peck, 1988). Even if there are economies of scale to be found increasingly in the secondary refinery business, they are much less pronounced than in the primary industry. On the demand side, the number of foundries is even larger, at approximately 2500 (EAA, 1996). Hence, a priori, it could reasonably be claimed that there is no market power by sellers or buyers in this market. This is said with the caveat that there might be buying power at the end of the demand chain—i.e. that automobile manufacturers might extort market power as being the largest users of foundry products made from secondary aluminium alloys.

The product of secondary refiners is heterogeneous, with refiners producing a wide variety of alloys, with different applications and different uses. However, we will abstract from these qualitative differences and choose to treat the market for secondary casting alloys as one, and the product as homogenous. Further subdivision of that market, according to alloy standards, only adds confusion and provides very little additional insight.

Pricing in the secondary aluminium alloy market

Equilibrium price in a competitive market is determined jointly by supply and demand. Here, we will describe some specific features considering the actual price formation in the secondary aluminium alloy market. First, it should be noted that in many metal markets—for example copper—secondary metal price and primary price are a linear combination of each other with the primary price regularly functioning, due to its generally greater flexibility in a number of uses, as a roof over which the secondary price never climbs. As the primary price increases, so does the demand for the secondary metal as being a near-perfect substitute. As can be seen from Fig. 2, this does not quite hold true for aluminium, where the German secondary price has indeed exceeded the primary price for some brief periods—for example, between 1990 and 1993. The same pattern can also be found in other European countries. This peculiar pattern can be explained by considering that pure primary aluminium has few applications as it is, especially in castings, but needs to be alloyed with other materials to get the required quality (Henstock, 1996). Also, even if the price of primary aluminium were to rise, there would be only a limited increase in the demand for secondary alloys, due to the limited substitutability of secondary aluminium in the production of wrought products. Secondary refiners could substitute primary aluminium for scrap as input in alloy production, but due to its relatively higher price, primary aluminium is usually used only as a “sweetener”. Second, secondary price and the scrap prices are both closely correlated and also highly volatile, with the German secondary producer price reaching a high of 70 ct/lb in real terms both in 1984 and 1989 and a low of 30 ct/lb in 1994. We can also note a decreasing margin between the scrap prices and the secondary price, indicating both decreasing profits for the industry and possibly growing scarcity of aluminium scrap material.

Third, considering the actual price setting, the German producer prices play an important role as an indicator. A second important indicator is the London Metal Exchange (LME) Aluminium Alloy contract introduced in late-1992. At first heavily criticized and overlooked,

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4 A considerable number of these were what we could define as marginal swing producers, starting production if prices are deemed sufficient to cover costs and ceasing it altogether if not. Defining those refiners with annual capacity below 1000 tons as marginal swing producers, approximately 60 refiners would fall under this heading.

5 There are innumerable different alloys. The two main “classes” are silicon- and copper-based alloys. The exact composition is determined by what type of casting technique is used by the foundry (and hence by the requirements of the final application).
Fig. 2. German aluminium metal producer prices 1983–97 (Real ct/lb*). Source: Organisation of European Aluminium Refiners and Remelters (OEA), 1983–98. *The World Bank G-7 deflator is used to calculate real prices, with 1980 as the base year.

It now seems to take an increasingly prominent role as an indicator. There are discussions within the industry to link scrap prices to the LME Aluminium Alloy contract to alleviate some of the pressure on the industry from the shrinking margin between secondary and scrap prices.

Input costs in the secondary refinery industry

Considering variable costs, the single largest cost for secondary refiners is that of raw materials, i.e. old and new scrap, and depending on what is included, scrap accounts for up to 70 percent of total variable cost (Gotthard Aluminium, Sweden, pers. commun.). The share of old scrap at secondary refiners usually varies between 30 and 40 percent, with the remainder being new scrap in different forms. The variation in shares is due to fluctuations in the relative price of old and new aluminium scrap, with new scrap usually being the more expensive, due to higher quality. The fluctuations in scrap prices are explained by the relative availability of old and new scrap. Scrap availability has been increas-

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8 Scrap intake statistics exist only for Germany, though the shares are likely to be more or less the same in other countries due to similarities in technology, pricing, etc.

5 The availability of new scrap is basically a function of the industrial activity, the composition of aluminium products currently made and the production technology used. This means that with high activity in the economy, more aluminium-containing products will be made, resulting in more trimmings, cuttings, etc. Also, with a high proportion in the system of products whose production results in a high share of scrap, the availability of new scrap will increase, and vice versa. On the other hand, over time, better and less wasteful production technologies will be applied, reducing the percentage of new scrap in the production process. Old scrap availability, however, depends on several concurrent factors, such as the reservoir of aluminium contained rigidly tight during the 1990s, due both to an increase in scrap export, especially to the Far East, and to increased competition from remelters (Gotthard Aluminium, pers. commun.). Remelters produce wrought alloys (rolling slabs and extrusion billets) and master alloys with special quality requirements on the input, which limit them to basically using new scrap. Since remelters usually receive a higher price for their product, and hence are able to pay a higher price for better quality scrap, secondary refiners have been increasingly forced to use old scrap to meet the decreasing margins.

An increasingly important cost factor is, broadly termed, "environmental costs". These costs include different abatement costs to reduce various discharges into air and water, noise reduction, etc., but, specifically for the secondary industry, deposition costs for salt slag.

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8 The most common technology in the secondary refinery industry is the oil- or natural gas-fired rotary furnace, which is well suited for recycling of low-grade scrap. The downturn is that a rotary furnace
All these costs vary in different countries across western Europe, depending on laws and regulations. For example, deposition costs in Sweden are approximately 300 SEK/ton, while in Denmark they are twice as high (Gotthard Aluminium, pers. commun.). Hence, total environmental costs are hard to estimate, but could in some countries, reach 20 percent of total cost (OEA, 1998).

When producing secondary aluminium alloys, there are a number of essential inputs needed to get the required alloy quality. The most important of these materials is silicon, which, depending on alloy specification, could be well over 10 percent of total material used. Of the cost for the materials used, silicon constitutes approximately 6–7 percent (Gotthard Aluminium, pers. commun.). Other important alloy materials include copper and magnesium.⁹ Due to the generally high wage levels in most West European countries, this is often one of the top cost items in a refinery, even though the industry is relatively capital intensive. Contrary to the primary industry where energy costs take second place after bauxite/alumina, oil and natural gas—which most secondary refineries in western Europe use—play a somewhat smaller role, especially during the period under consideration here with its low oil prices.

The demand for secondary aluminium alloys and castings

The single largest customer of secondary castings is the foundry industry, which takes approximately 80 percent of the secondary refinery industry’s production (Kirchner, 1992). Hence, the input of the foundry industry demand will, to a great extent, determine how much the secondary refinery industry will be able to sell. The foundries buy the secondary alloys mostly by short- to medium-term contracts with the refineries.

However, as for all metals, the demand for secondary aluminium is derived from what goes on in the end-use stage. If the demand at any end-use stage changes, in content and/or volume, it will inevitably change the conditions for the metal industry itself. Therefore, in the case of the secondary refinery industry, we must also consider the automobile industry. In countries like Germany, France, Italy and the UK, all with domestic automotive industries, the transport sector’s share of secondary aluminium cast consumption ranged from 58 percent in Italy to almost 85 percent in France in 1997 (OEA, 1997). Even though the European automobile industry is not likely to grow at a rapid pace over the next few years, increasing demands on fuel efficiency make for a favorable prognosis for increased penetration of aluminium, being a lightweight material. Tessieri and Ng (1995) forecast a 75 percent increase in the use of cast aluminium in cars between 1991 and 2000. Currently, cast aluminium products constitute only a small fraction of the total vehicle cost, making the auto manufacturer unlikely to shift rapidly from one material to another. Also, material substitution possibilities in the short to medium run are probably not very significant, because of expensive re-tooling of production facilities and the fact that product designs might demand certain materials, making it possible to change material only when the entire design is changed.¹⁰ Possible substitutes in vehicle engines include cast iron, steel, magnesium and composite materials. The auto industry’s large share of secondary aluminium alloy use indicates a possibility for monopolistic buying behavior, especially since some manufacturers have their own foundries, such as, for example, VolksWagen. In this paper we will not explicitly treat this possibility in any other way than as a caveat to remember. It should also be noted that auto production and sales are correlated with the general business cycle. Fluctuations in GDP will, therefore, inevitably trickle down to the secondary refinery industry with some lag.

Theory and model

Short-run price determination in a perfectly competitive market

In this part, we outline briefly the partial equilibrium supply and demand model,¹¹ which will serve as a framework for the coming analysis. A perfectly competitive market must obey a number of restrictions, such as a large number of profit-maximizing firms producing a homogenous good. Firms are price-takers, i.e. they have no individual influence on price. Prices are transparent and known to the market participants. Finally, in the short run, the number of firms is fixed, i.e. no entries or exits are allowed. At firm level, the optimal, or profit-maximizing, output is where the firm’s marginal cost of production equals the market price. In the short run some costs of production are fixed, for example capital; hence, no alteration of their quantity is possible. Instead, firms are assumed to choose the optimal quantity of variable inputs, such as labor and raw materials, to produce the profit-maximizing output. Production will continue as

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⁹ Some of the copper needed is extracted from the scrap processed by the refineries. Magnesium, it should be noted, is both a complement in production and a possible substitute in casting production for the auto industry.

¹⁰ For example, in the auto industry, the substitution between materials could probably only be done when changing model or engine generation, which occurs approximately 6–10 years apart.

¹¹ For a more thorough treatment of the competitive market and the firm, see any textbook on economics. For example, Nicholson (1997) contains an excellent treatment.
long as the going market price covers the average variable costs, and will cease whenever price sinks below this threshold. The market supply is derived by simple horizontal summation of the individual firm’s supply schedules, which is represented by their marginal cost curves above their average variable costs.

Let the market supply be represented by the following equation:

$$QS = f(P, \alpha)$$  \hspace{1cm} (1)

where $QS$ is the quantity supplied to the market, $P$ is the own price of the product and $\alpha$ is a vector of input prices for factors of production that are variable in the short run. The own price effect, $\partial QS/\partial P$, is assumed to be positive, i.e. an increase in price increases the quantity supplied. The effects of input price changes, $\partial QS/\partial \alpha$, are generally negative. With the same type of reasoning, the market demand could be modeled as:

$$QD = f(P, \beta, \delta)$$  \hspace{1cm} (2)

where $QD$ is the quantity demanded on the market, $\beta$ is some income or activity variable and $\delta$ is a vector of substitute prices. Here, the own price effect, $\partial QD/\partial P$, is negative. The higher the price, the less the quantity demanded. The income effect, $\partial QD/\partial \beta$, and the substitution effects, $\partial QD/\partial \delta$, are both positive. Finally, equilibrium requires that

$$QS = QD$$ \hspace{1cm} (3)

From this, we can see clearly that equilibrium quantity and price are decided simultaneously in the market. With this model the effect on quantity supplied and demanded from changes in the exogenous variables can be studied. Also, changes in the equilibrium price, caused by some change in any of the exogenous vectors $\alpha$ and $\delta$ and the variable $\beta$, can be studied. Changes in equilibrium price are derived by means of comparative statics (see, for example, Chiang (1984) for a complete treatment).

Based on what has been said above, we will develop a simple econometric model of secondary aluminium supply and demand. The model will be applied to four West European countries, namely Germany, France, the UK and Italy. These countries have been selected for three reasons. First, together they produce approximately three-quarters of the West European total of secondary aluminium from refiners. Second, they all have significant auto industries, and hence have major domestic end-users of secondary aluminium castings.\footnote{They occupy places one, two, four and five, respectively, in size-ranking among European auto-producing nations. Spain is number three, surpassing both the UK and Italy. However, Spain’s secondary refinery industry is less than half the size of, for example, that of the UK.} Third, data availability is very limited for other European countries.

We proceed by first presenting the “complete” model that would be applied under ideal circumstances. We continue by discussing the data used and presenting the econometric specification.

**The “ideal” model**

Let supply and demand in the secondary aluminium market be represented by the following general equations (the expected direction of influence on supply and demand of the respective variables is listed under each variable):

$$QS_t = g(P_{GS}, P_{MAG}, P_{SIL}, P_{AP}, P_{NS}, P_{MAG}, P_{CAP})$$ \hspace{1cm} (4)

and

$$QD_t = -g(P_{GS}, P_{MAG}, P_{SIL}, P_{AP}, \text{GDP}_t)$$ \hspace{1cm} (5)

In Eq. (4), $QS$ denotes the production of secondary aluminium by refiners, and $P_s$ is the price of secondary aluminium alloy. Input prices are denoted by $P_{GS}$, $P_{MAG}$, $P_{SIL}$, $P_{AP}$, $P_{NS}$, $P_{MAG}$ and $P_{ENV}$ which represent the price of old scrap, price of new scrap, price of silicon (a complement), wages, price of fuel oil and environmental costs, respectively. Finally, $CAP$ measures refinery capacity.\footnote{Since this is a short-run model, we assume that capital, i.e. production machinery, is fixed. Hence, supply responses could come only from changes in variable inputs. Therefore, some physical measure for capital has to be introduced.} Quantity demanded of secondary aluminium is $QD$ in Eq. (5). The price of magnesium, a possible substitute for aluminium in certain auto applications, is represented by $P_{MAG}$.\footnote{One should be aware that there exist many possible substitutes depending on the specific application. Examples are cast iron, steel and copper. Thus, there is no clear-cut single substitute material for aluminium.} Further, $AP$ represents auto production and GDP is the gross domestic product. Finally, $i$ denotes country and $t$ time.

**Data and econometric specification**

The data used to estimate the model cover Germany, France, Italy and the UK over the period 1983–97. Country data on secondary aluminium production are taken from OEA annual reports (OEA, 1983–98) and the World Bureau of Metal Statistics annual yearbook (1970–95). The price used for secondary aluminium is the national price of copper-containing alloys, and is...
taken from the OEA.\textsuperscript{16} Input prices for old and new scrap are for old cast scrap and new pure cuttings respectively, also from the OEA. Since the prices of old and new scrap are closely correlated, a weighted average is calculated to avoid multicollinearity problems.\textsuperscript{17} All aluminium prices are measured in US cents (ct)/lb. Labor costs for Germany and the UK are taken from the International Labor Office, Yearbook of Labor Statistics, 1983–97, and are measured as the hourly wage rate in the local currency for workers in the non-ferrous metal basic industries (ISIC code 372). For France, labor costs are from Eurostat (1998) and measure hourly wage rates in the basic metal industry. For Italy, only an hourly compensation index for industrial workers was accessible from the Bureau of Labor Statistics (International Labor Statistics, 146.142.4.24/cgi-bin/surveymost 1999-02-12). All wage costs have been calculated in USS and transformed into indexes. All prices have been deflated with the World Bank G-7 deflator using 1980 as the base year. Since no capacity measures were available for the time period, taking the maximum production in each country five years back generated a crude measure of capacity. In an expanding industry such as the secondary aluminium industry, this, however, often coincides with current production. Automobile production statistics are taken from the United Nations Industrial Commodity Yearbook (1983–97) and cover the production of passenger vehicles only. Data on environmental costs and other inputs, such as silicon, are either not available at all, as in the case of deposition cost for salt slag, or as for silicon prices, only available for parts of the period and for some of the four countries. The same is true for magnesium prices that were available only for Italy on a consistent basis. Because of the lack of consistent data on silicon and magnesium prices and environmental costs, we were forced to exclude these variables from the final econometric specification.\textsuperscript{18}

Given the above, the final model specification to be estimated is:

\[
\ln QS_i = \delta_0 + \phi_1 \ln P_{SCi} + \phi_2 \ln P_{SAl} + \phi_3 \ln W_i + \phi_4 \ln CAP_{P} + \phi_5 \\
+ \phi_6 \ln CAP_{f} + \phi_7 \ln CAP_{u} + \phi_8 \ln CAP_{m} + \phi_9 \ln CAP_{d} + \phi_{10} \ln CAP_{o} + \phi_{11} \ln CAP_{s} + \phi_{12} \ln CAP_{t} + u_i 
\]

(6)

where \( \delta_i, \phi_i, \) and \( \alpha_i \) are constants, \( P_{SC} \) is the weighted scrap price (as described in \textsuperscript{17}) and \( \phi \) and \( u \) are the error terms.\textsuperscript{19} All other variables are defined as in Eqs. (4) and (5). Since we wish to interpret the coefficients of the model as elasticities, the model is in log linear format.\textsuperscript{20}

Results and analysis

Empirical results

Since price and quantity are determined simultaneously, ordinary least square (OLS) estimates would be biased and inconsistent, and the statistical tests invalid. Hence, we will apply the so-called two-stage least square (TSLS) regression technique to account for the simultaneous equation bias in the estimation procedure (see, for example, Dougherty (1992) for a basic treatment of the simultaneity problem and the TSLS technique). To account for heteroscedasticity—due to the difference in absolute size between the different countries’ secondary aluminium industries—we apply weights to the equations (estimation by weighted two-stage least square (WTLSLS)) (see, for example, Greene (1997)). Since we have data both for the four countries and over a specific time period, we pool observations into a panel set-up. The fixed effect approach (see \textsuperscript{19}) means we get a single (common for each country) elasticity for each variable. Hence, by using fixed effects, we implicitly assume that the four countries in the study

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\textsuperscript{16} Alloy specification may vary between countries. For Germany, France, Italy and the UK, the alloys are Leg 226, A1963, GD Al Si 8, Sca3, 5 Fe and LM24, respectively.

\textsuperscript{17} The weighted price of scrap, \( PSC \), has been calculated using the scrap intake shares of German refineries. The formula used is \( PSC = (\text{share of old scrap at time } t \times \text{price of old scrap at time } t) + (\text{share of new scrap at time } t \times \text{price of new scrap at time } t) \). By doing this, we implicitly assume that the mix of old and new scrap and hence also the technology in France, Italy and the UK are similar to those in Germany. The weighting exercise is mainly done to take care of some of the multicollinearity problems concerning prices.

\textsuperscript{18} The effect of missing variables could, however, lead to biased coefficient estimates. For example, the lack of a clear-cut substitute price (in both a technical and a statistical sense) can result in a bias estimation of the demand price elasticity. If a coefficient for a substitute input could be included this would, at least according to theory, be positive. If, in addition, we had a positive correlation between the own price and the substitution price, it can be shown that the estimated coefficient of the own price is upward biased if we exclude the substitution price. For more on this issue, see for example Dougherty (1992).

\textsuperscript{19} To estimate Eqs. (5) and (6) (using pooled time series and cross-section data) we apply the so-called fixed effect model. The fixed effect model assumes that any differences across units can be captured in differences in the constant term for each country. Such differences will be captured by the use of an additive disturbance term \( u_i \) (where \( i \) denotes country and time). This disturbance could further be decomposed into two parts such as \( u_i = \gamma_i + \bar{u}_i \), where \( \gamma_i \) accounts for the unobservable time-invariant country-specific error not included in the model, while \( \bar{u}_i \) varies with both time and country and thus could be regarded as the usual error term. The country-specific error \( \bar{u}_i \) may be interpreted as any unobserved fundamental difference among the different countries’ secondary aluminium supply or demand. By assuming that these disturbances are fixed over time, we are able to eliminate them by introducing a dummy variable for each country. For an advanced and thorough treatment of panel data estimation see Baltagi (1995).

\textsuperscript{20} The log format enables us to interpret the coefficients of the independent, or explanatory, variables in the equations as a percentage response of the dependent variable to a one percentage change in any of the independent variables.
share the same basic characteristics, such as production technology. Finally, due to initially low Durbin–Watson values, indicating autocorrelation, the regression was run in AR(1) mode. The results of the regression are shown in Table 3.

As can be seen from Table 3, the signs of the estimated coefficients, with one exception, all coincide with the expected ones. Furthermore, Table 4 shows that, with the exception of German secondary supply, our simple model explains from 60 to well over 90 percent of the observed variation. The price elasticity of demand, which, according to economic theory, should be negative, obtained a positive sign, however insignificant. Even if it is positive, it is quite close to zero, indicating inelastic behavior. This is reasonable since we are analyzing changes in the short run, when demand is more focused on production commitments, and responsiveness to price changes by the foundry industry is hence likely to be marginal. Also, substitution possibilities for the foundry industry are likely to be marginal. If 1 percent increase in auto production raises the demanded quantity by 1 percent, the demanded quantity increases by 0.5 percent, but what is the effect on equilibrium price? It can be shown that this effect is 

$$\frac{0.52}{0.07} = 7.38$$

That is, a 1 percent increase in auto production raises the demanded quantity of secondary aluminium alloys by slightly more than 0.5 percent.

### Some comparative static results

In the discussion above, we are able to see the implications on the quantity supplied or demanded of secondary alloys. What might, however, be more interesting is the effect on equilibrium price of the alloy from a change in auto production or a change in input prices. If auto production increases by 1 percent, the demanded quantity increases by 0.5 percent, but what is the effect on equilibrium price? It can be shown that this effect is 

$$\frac{-0.52}{0.07 - 0.17} = -3.1$$

That is, a 1 percent increase in auto production raises the equilibrium price by 5.2 percent. As a result of our positive demand elasticity, this effect is quite significant, because the price increase does not reduce the equilibrium price. If we instead assume zero response to price, i.e. a totally inelastic demand, the change in equilibrium price would instead be 

$$-0.52 / (-0.17) = 3.1.$$
Table 4
Regression statistics for individual countries

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Supply</th>
<th>Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Germany</td>
<td>France</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.45</td>
<td>0.90</td>
</tr>
<tr>
<td>Durbin–Watson</td>
<td>2.13</td>
<td>2.76</td>
</tr>
</tbody>
</table>

The equilibrium price by 3.1 percent, which is still quite significant. These results could be motivated by the fact that in the short-run there are few, if any, substitution possibilities for the auto manufacturers. Also, the low cost share of secondary aluminium in the final automobile production cost probably makes auto manufacturers rather insensitive to at least moderate price increases. This result should, however, be interpreted with some caution, due to the possibility of the existence of buyer power on the auto manufacturer side.

In the same way, it can be shown that a 1 percent increase in the price of scrap increases the equilibrium price by 0.6 percent. Hence, the margins of secondary refiners would decrease, since they cannot raise the price of secondary alloys to cover the full cost increase.

Conclusions and policy discussion

In this paper we set out to identify the different factors determining supply and demand of secondary aluminium alloys in the short run. Using data from Germany, France, Italy and the UK for the time period 1983–97, the relative importance of the identified factors were then assessed. Our simple model, we conclude, fits quite well in describing the market for secondary aluminium alloys, as could be seen from the relatively high $R^2$ values in Table 4 (with the caveat mentioned above considering the possibility of excluded variable bias). The results imply both inelastic demand and supply behavior, which is fairly reasonable considering that we are dealing only with short-run changes. The type of industry that secondary refineries represent, with fairly high capital intensity, makes short-run adjustment of supply difficult. Also, secondary supply is insensitive to changes in input prices. For example, due to commitments to its customers, cost increases due to higher scrap prices have little effect on secondary supply from the refineries, at least in the short run. Furthermore, our results indicate a relatively high responsiveness in some of the exogenous variables, such as auto production and capacity. As an effect of the low price elasticities, we have shown that the effect on equilibrium price from a change in automobile production is relatively significant (a 1 percent increase in automobile production tends to increase the secondary aluminium price by approximately 3 percent). This seems to be in line with the high volatility in secondary alloy prices.

Firm conclusions about proper policies, for example how increased aluminium recycling should best be stimulated (if we believe such a goal is socially worthwhile), are hard to draw, considering our model is only for the short run. However, our results, albeit tentative, indicate that policies aimed at increasing aluminium recycling by manipulating price (for example, subsidies aimed at increasing the price received by secondary refineries) will be inefficient considering the low own-price elasticity of secondary supply. Policies aimed at decreasing the cost of recycling, for example by making scrap cheaper (for example, by public investment in better scrap collection and pretreatment infrastructure, or by demands on products to be designed for recyclability), will also run the risk of not getting the job done, as the low supply response to changes in scrap prices indicates. Policies not directly aimed at recycling might turn out to do better. For example, a speculative suggestion is that increased public and private demands for better fuel efficiency and safety in cars might potentially increase the demand for materials, such as aluminium, with a favorable strength to weight ratio. Considering the already strong position of secondary aluminium within the transport sector of the economy, deeper penetration and increased demand of secondary aluminium is thus a possibility. This, however, hinges on the secondary refinery industry competitive position vis-à-vis the primary aluminium industry and other materials.

Further research is needed to fully understand the secondary aluminium alloy market. First, some measure of the excluded, but theoretically motivated, variables would increase the precision of the estimated coefficients. Second, the model should be expanded to a long-run format to gain a better understanding of market behavior. This would, for example, include capital prices and a more explicit treatment of the end-use structure of aluminium and its influence on the accumulation of scrap. Thus, a measure of the availability of scrap should be developed. Also, some measure of technology developments in the industry would be preferred. The effects on West European secondary aluminium production from trade in both scrap and secondary aluminium alloys should, perhaps, also be included in an extended model.
References

Economic Models of Secondary Aluminium Pricing and Supply

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Abstract: Due to the high value of scrap metals, recycling of copper, aluminium etc has been undertaken for as long as these metals have been used, and regardless of any policy initiatives. The fact that metals are recycled in the absence of public policies, gives rise to a number of questions. What factors determine the amount of metal supplied from scrap, and what is the economic significance of these factors? How does the market for secondary metals interact with the market for primary metals? The proper understanding of such questions is important. If we believe that there is insufficient metal recycling undertaken, and hence that it should be stimulated, knowledge about the market in question is important for the formulation of efficient public policies. Given the questions posed above, the general purpose of this paper is to identify the fundamental economic forces driving the pricing and the supply of aluminium made from scrap. First, a simple model of pricing is considered. This accounts for the interdependencies between the primary and the secondary sectors of the aluminium industry. Second, a theoretical model of secondary aluminium supply is developed. This model integrates microeconomic theories of production and cost with a simple dynamic model of scrap generation and accumulation. The parameters of the supply model are estimated in two different ways. In the first case, we explicitly include input costs for scrap. However, since the input price of scrap is not independent of the output price of secondary aluminium alloys, the resulting own price elasticity tend to be overestimated. Thus, a second, alternative supply function accounting for this is also estimated. We estimate the models using pooled cross-section and time-series data for four Western European countries, Germany, France, Italy and the United Kingdom, for the years 1983-97. The results indicate that the primary exchange price is an important determinant of the secondary aluminium price, along with overall industrial activity. Furthermore, the supply response to changing own prices is low (0.21) and the effect from the stock of scrap is small (0.07). We conclude that price affecting policies to stimulate additional recycling of aluminium will lead only to small increases in recycling rates.

Keywords: Secondary aluminium; Aluminium recycling; Scrap stock; Cobb-Douglas cost function; Panel Data; Western Europe

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INTRODUCTION

During the 1980s and 1990s, recycling of a wide array of materials, ranging from food product waste to advanced products such as cars and computers has become part of everyday life. Recycling, it is claimed, saves resources, decreases the need for landfill space and enhances environmental awareness among the public (Ackerman, 1997). When considering non-renewable resources such as metals, recycling also prolongs the period it takes to deplete the resource. The claimed benefits have brought forward a manifold of policies to stimulate the activity, examples being public investment in recycling infrastructure (such as collection centers) and target levels for recycling rates set by authorities. The increase in public policy efforts creates the impression that there is not enough recycling done in society, i.e., that we should recycle more. Without appropriate policies there would be no or too little recycling undertaken, indicating that, in the mind of public policy makers, recycled materials have little positive economic value.

Recycled metals, however, do have a commercial value, and are recycled because it is profitable to do so. They represent a cheap source of raw materials compared to primary metal, since most of the costs for exploration, mining and primary refining have already been taken. Furthermore, recycled metal is often a near perfect substitute for primary metal since the properties of metals (i.e., ductility, conductivity etc) usually are not lost when the metal is used and finally scrapped. Thus, there exists an incentive to recover and recycle scrapped metal for sale in a market. For this reason, metal recycling has been undertaken almost as long as metals have been used, and the metal recycling industries today contribute a sizeable proportion of metals consumed. For example, in 1993 out of the total amount of aluminium, copper, lead and zinc consumed in the western world, approximately 24, 51, 53 and 28 percent respectively is recycled material (Metal Statistics, 1994). Hence, recycling of metals is, at least to some extent, driven by economic considerations, such as price and cost, and not as in the case of some other recycled materials, such as food or garden waste, primarily by policy. The assertion that markets for recycled metals exist regardless of policy gives rise to a number of questions. For example, what factors determine the amount of metal supplied from scrap, and what is their economic significance? In what way does the market for secondary metals interact with the market for primary metals? The proper understanding of these problems is important. If we believe that there is insufficient metal recycling undertaken, and hence that it should be stimulated, knowledge about the market in question is important for policy purposes.
Given the questions posed above, the general purpose of this paper is to identify the fundamental economic forces driving the pricing and supply of aluminium made from scrap. To do this, a theoretical model of secondary aluminium recovery and recycling is developed, integrating microeconomic theories of production and cost with a dynamic model of scrap generation and accumulation. In addition, a simple model of pricing will be considered; it accounts for the interdependencies between the primary and the secondary sectors of the aluminium industry. The models are estimated using pooled cross-section and time-series data for four European countries, Germany, France, Italy and the United Kingdom over the time period 1983-97. Our selection of metal and countries is motivated by a number of reasons.

First, aluminium is today the most important non-ferrous metal with consumption more than twice that of copper. Aluminium use, both in tonnage and in number of applications, has also experienced a more rapid growth than have most other major metals since World War 2 (e.g., Crowson, 1996).

Second, as Table 1 demonstrates, secondary aluminium has come to play an increasingly important role in western European supply. This is primarily because increasing energy costs have made primary production in Europe less profitable after the oil crises in the 1970s. Secondary aluminium production in Western Europe represents almost 40 percent out of primary production in 1997. The relevance of the secondary industry is even more pronounced in some countries. In Germany, for example, the secondary aluminium industry accounts for three-quarters of domestic supply, and in Italy it constitutes more than twice that of primary production. Consumption-wise, secondary aluminium provides approximately a quarter of the aluminium used in Western Europe, a share that has been remarkably stable over time.

Third, earlier research on metal recycling has focused on copper recycling. Exceptions include Slade’s (1979, 1980b) studies of copper and aluminium substitution and recycling and Carlsen’s (1980) study of causes to fluctuations in aluminium recycling rates. However, both Slade and Carlsen focus, as do most earlier quantitative research efforts concerning metal recycling, on the US market. The US focus in earlier literature is most likely due to lack of comprehensive data in other parts of the world. Blomberg and Hellmer’s (2000) recent study of the secondary aluminium market in Western Europe is, however, a rare exception.

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It should be noted that the proposed models only consider aluminium recycling that is assumed to be (privately) economically motivated. Thus, we do not attempt to explore whether the amount of aluminium recycled is optimal or not from a societal perspective.
Table 1: Western European Aluminium Production and Consumption 1) (thousands of tons)

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<tr>
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<tbody>
<tr>
<td>Primary Production</td>
<td>1841.2</td>
<td>3377.2</td>
<td>3323.9</td>
<td>3042.7</td>
</tr>
<tr>
<td>Secondary Production</td>
<td>814</td>
<td>1202</td>
<td>1708.6</td>
<td>1851.1</td>
</tr>
<tr>
<td>Apparent Total Consumption</td>
<td>3211.6</td>
<td>4767.8</td>
<td>6515.4</td>
<td>7595.8</td>
</tr>
<tr>
<td>Secondary Production/ Total Production</td>
<td>0.307</td>
<td>0.263</td>
<td>0.339</td>
<td>0.378</td>
</tr>
<tr>
<td>Secondary Production/ Apparent Consumption</td>
<td>0.253</td>
<td>0.252</td>
<td>0.262</td>
<td>n.a.</td>
</tr>
</tbody>
</table>

1) Excluding Yugoslavia, Greece and Iceland
2) 1995 figures


In distinction to the Blomberg and Hellmer (2000) study, this paper accounts for price formation in the secondary aluminium market and thereby the interaction between the primary and secondary aluminium markets. Furthermore, in this paper we build our supply function on an explicit Cobb-Douglas formulation. We also include other important cost items such as energy and capital. Moreover, we explicitly account for the scrap accumulation process and develop a measure of scrap availability. This measure enables us to estimate the effect on secondary aluminium supply from changes in scrap availability. Fourth, our choice of countries is motivated both by their large share of West European secondary aluminium production (75 percent of total production in 1997), and by data availability.

The paper proceeds as follows. In the next section a brief description of the aluminium industry in Western Europe is presented. The different flows and sources of material are described, and the linkage between the primary and secondary industries is discussed. The structure of aluminium end use is also briefly examined. Although the presentation is general in scope, the emphasis is on the secondary aluminium market in Western Europe. In the following section our models of the secondary aluminium market are presented. Equations for price formation, supply of secondary aluminium and scrap generation are outlined. The data used and the econometric estimates are presented and analyzed in the subsequent section. We then propose an alternative model of secondary supply, partly based on the results achieved in the preceding section. In a final section, the empirical results are discussed and some concluding remarks are provided.
THE SECONDARY ALUMINIUM MARKET IN WESTERN EUROPE

Figure 1 shows a simplified representation of the aluminium market. Aluminium metal can be produced either from bauxite or from scrap - by the primary industry in the former case and by the secondary industry in the latter. The metal (in ingot or molten form) is delivered to intermediate producers such as mills, foundries or powder plants that produce rolled and extruded products, castings and other products for end use in the manufacturing industries. The sheets, casting ingots etc, are then delivered to the building, transport, engineering and packaging industries who produce products for final consumption. After retirement, the aluminium products are scrapped and returned to the flow of metal, or discarded in other ways, for example in landfills. Throughout this paper we will focus on the scrap–secondary industry route (marked by bold arrows in Figure 1). Therefore we will scrutinize some aspects of this industry in detail before proceeding.

![Figure 1. The Aluminium Market](image)

**Industry definition and structure**

Depending on the definition, the concentration of the West European aluminium recycling industry ranges from several thousands actors if we include both scrap collectors, scrap merchants, remelters and refiners. This paper focuses entirely on the refinery sector of the aluminium recycling industry. By the end of the 1990s there were approximately 200 secondary refineries operating in Western Europe. Even with this narrow definition, the

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2 Thus, the statistics in this paper exclude direct use of scrap by primary smelters and remelters and pertain only to the production of aluminium by the secondary refiners.
European secondary aluminium industry is much less concentrated compared to its primary counterpart. The focus on the refinery industry is necessitated by the lack of statistics regarding scrap recovery, but it is also motivated by the central role played by the refineries in the recycling process.

The refineries range from small firms producing under 1000 tons annually, to large industries with capacities well above 50,000 tons (OEA, 1998). Among the major secondary aluminium producing countries, the German refinery industry is the most heavily concentrated with 13 companies (Ibid.), with only two producing under 10,000 tons on a yearly basis. In France, the four biggest plants (out of 26) accounted for approximately 50 percent of annual production and the ten biggest for 75 percent (Ibid.). In the UK and Italy, the two other major European producers, the industry structure is much more scattered, with a large number of small producers. Perhaps a more meaningful definition of the market would include not only the production of secondary refiners, but the output of primary producers as well, since primary and secondary aluminium are substitutes, at least to some extent. Thus, the secondary refinery industry could be viewed as the competitive fringe to the oligopolistically organized primary industry. This will be illustrated in more detail when we discuss price formation in this market (see below).

Sources of Scrap
The secondary refinery industry uses scrap aluminium as its chief input. Aluminium scrap can, as Figure 1 shows, be divided into two main types depending where it arises in the flow. New scrap (or prompt-, process or manufacturers scrap) arises and is recovered during all stages in the manufacturing chain, from original smelting and refining through semi-production to the production of final goods, regardless of whether the products are made from primary or scrap metal. Examples are clippings, borings and trimmings or the skeleton remaining after can lids are stamped out of aluminium sheets. The volume of new scrap is hence closely linked to the level and technology of manufacturing of aluminium containing products. Almost all new scrap is recovered and recycled, both due to its (usually) known metallic composition and hence high value and the high costs of storing it at the facility where it arises, or alternatively deposit it in landfills. Home scrap (or run-around-, revert- or in-process scrap) also arises during smelting or refining of both primary and scrap aluminium.

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3 It is difficult to calculate concentration ratios since available capacity figures only give ranges and not specific numbers. Also there exist no official plant production data published.
Home scrap, though, never enters the market; it is instead recycled within the production facility from which it originated. Hence home scrap is of little interest for this study.

The third source of scrap depicted in Figure 1 is so called old scrap (or obsolete-, capital-, or country scrap). Old scrap is recovered from end use products, such as automobiles, window frames, used beverage cans (UBC) etc, reaching the end of their useful life. The aluminium content in all previously manufactured end use products makes up the pool of potentially recoverable material. Usually, old scrap is of lower grade than new scrap, since the material composition of worn out products often is both complex and less well known. Aluminium UBCs’, for example contain two different alloys, one for the lid and one for the body of the UBC, hence demanding different types of treatment. Old scrap therefore demands a more rigorous treatment than that of new scrap before a secondary refiner can utilize it. This service is usually performed by the recovery industry in the preceding stage to refining, i.e., a large number of scrap collectors and merchants sorts and upgrades the scrap according to metal content and quality, package it into “bundles” and finally market it.

Secondary refiners refine scrap of highly various qualities, i.e., both new and old scrap. This is in contrast to primary producers and remelters that require purer raw material inputs (i.e., new scrap). Secondary refiners compete especially with remelters for new scrap of high quality (remelters produce wrought products, hence they have higher demands on the scrap material they use a have secondary refiners). Due to the mixed quality of most post consumer scrap, secondary refiners, however, remain the prime buyers of old scrap.

End Use Structure

The product of secondary refiners - secondary aluminium alloys - comes in either ingot or is delivered in liquid form, and is used mainly for casting products and steel deoxidants. Cast alloys are by far the most important of these products. The single largest buyer of secondary cast alloys is the foundry industry, which takes approximately 80 percent of the secondary refinery industry’s production (e.g., Kirchner, 1992). The foundry industry in turn makes a wide variety of intermediate products, mainly for the automotive industry. In countries like Germany, France, Italy and the UK, all having domestic automotive industries, the transport sector’s share of secondary aluminium cast consumption range between 58 percent in Italy to almost 85 percent in France in 1997 (OEA, 1997). Other important sectors include, for example, general and electrical engineering and building and construction.
When discussing secondary aluminium price determination we must examine the pricing of primary aluminium as the two are closely correlated. A high correlation indicates that primary and secondary aluminium are close substitutes. However, this claim comes with a caveat, necessitating a closer scrutiny of the relationship between primary and secondary aluminium especially considering the extent of their interchangeability.

In many metal markets – for example the copper market – secondary and primary metal are close substitutes. The scrap metal could be purified back to primary quality (or at least close to), and hence compete with the virgin metal in most applications. As the primary price increases so does the demand for the secondary metal, given that the two are near perfect substitutes. Thus, because of the high degree of substitutability, primary and secondary prices are usually linear combinations of each other. Being slightly less versatile, secondary metals are usually sold at a discount compared to its primary counterpart.

The relationship between primary and secondary aluminium is, however, not as clear-cut. For technical reasons, primary and secondary aluminium are only to a limited extent substitutes and therefore partly have separate markets. Pure primary aluminium currently has few applications, but could due to its purity be alloyed in whatever fashion wanted and used in both wrought and cast applications (e.g., Henstock, 1996). Secondary aluminium, on the other hand, cannot usually be purified back to original quality, and can therefore not offer substantial competition with primary aluminium in the wrought market, but is mainly used in castings. So, while primary and secondary alloys are substitutes in the cast market, primary aluminium is left to dominate in the wrought market. Thus, even if the price of primary aluminium would rise there would be only a limited increase in the demand for secondary alloys, mainly from the casting sector. The division between the two markets has, however, begun to weaken during the 1980s and 1990s, due to, for example, more flexible recycling technologies.

The primary price is, however, still a leading indicator for all other aluminium prices. Figure 2 shows the fluctuations of the German primary and secondary prices, the German price of old and new aluminium scrap, and the London Metal Exchange (LME) primary

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4 The German secondary price also plays an important role in the actual price setting of secondary aluminium in Western Europe. Since late 1992, the LME provides an aluminium alloy contract, which gradually has become another important indicator for the secondary alloy price. However, the LME alloy contract has been heavily criticized and debated by the secondary aluminium market participants and it is only recently that it has gained any significant acceptance as an indicator.
aluminium price on an annual basis. We can here clearly observe that they all are closely correlated.\(^5\), \(^6\)

\[\begin{array}{c}
\text{Price New Scrap} \\
\text{Price Old Scrap} \\
\text{Price Secondary Aluminium} \\
\text{Price Primary Aluminium} \\
\text{LME Primary Price}
\end{array}\]

Figure 2. German Aluminium Prices and the LME Primary Price

Sources: OEA and Metal Statistics

Exchange prices fluctuate with short run changes in supply and demand and inventory swings and are thus volatile in nature. The introduction of the LME aluminium contract in 1979, in combination with decreasing market concentration among primary producers, has decreased the influence of national primary prices. It is further shown in Figure 2 that, in the 1990s, primary prices have tended to fluctuate in accordance with the exchange price. The price we are principally interested in, the secondary price, also fluctuates with movements in the primary exchange price. For example, the correlation between the German secondary alloy price and the LME primary price is 0.7. An even higher correlation of 0.96 is found between the German primary price and the LME primary price. Similar high correlations between the national prices of the other major West European countries and the LME price can also be shown. It should be noted that the secondary price indeed exceeded both the producer and the LME primary price in the beginning of the 1990s. However, it could be

\(^5\) When comparing the prices included in Figure 2, one caveat should be noted. While the price for secondary aluminium is an alloy price (in this case a copper alloy), the price for primary is for 99.5 percent pure aluminium, i.e., unalloyed quality. We are therefore not comparing exactly the same aluminium qualities.

\(^6\) We have chosen to present the German prices here, both because Germany has the most important aluminium industry in Europe and because the German secondary price is an important indicator in the European secondary aluminium market. A similar picture would, however, emerge if we had chosen to graph the corresponding prices in any of the other major aluminium producing countries of Europe.
claimed that this gap cannot become too large or too extended over time, since that would induce the foundry sector to substitute primary aluminium for secondary alloys.

MODELS OF SECONDARY ALUMINIUM PRICING AND SUPPLY

Slade’s Copper Recycling Model

Since the model used in this paper draws on the work of Slade [1980a] we will briefly present the general idea behind her copper-recycling model. Before turning to her model it should be noted that there are few works that concentrate specifically on the functioning of secondary metal markets. Out of the studies that do exist, most focus on copper. In addition, almost all are studies of the US market. Among copper recycling studies we have Bonezar and Tilton (1975), Slade (1980a, 1980b) (of which the latter examines both copper and aluminium) and Stollery (1983) who examines both copper and iron/steel recycling. Aluminium recycling studies include Carlsen (1980) and Blomberg and Hellmer (2000). The latter is one of the few that analyzes metal recycling in Europe. Since recycled metal has always represented a significant share of metal consumed, numerous models of metal markets, aimed at chiefly examining primary supply nonetheless contain equations for secondary and/or scrap metal supply. Examples of such studies are the copper studies of Fisher et al. (1972) and Wagenhals (1984) and the study of the aluminium industry by Charles River Associates (1971).

Slade (1980b) uses a Cobb-Douglas cost function to identify the determinants of copper recycling in the USA for the period 1954-1976. She treats the secondary copper industry (including both scrap dealers and secondary refiners) as the competitive fringe to an oligopolistic primary copper industry, i.e., the entire secondary industry, and not just the individual refiner, is a price taker. The price of secondary copper is said to be a function of the primary producer copper price (as secondary and primary copper are perfect substitutes), some measure of economic activity and a one period lagged own price (to capture possible under- or overshooting effects). Secondary price, in her model, fluctuates to absorb any excess demand caused by sluggish primary supply. Supply of secondary copper from old scrap is modeled as a function of secondary price, a vector of input prices (of which scrap is the most important) and recovery efficiency (defined as the share recovered out of available scrap stocks). The definition of recovery efficiency indicates that marginal production (recycling) costs would rise with increased recovery due to utilization of lower grade scrap.

---

7 Thus, the statistics in her essay include both the direct use of scrap copper by primary smelters and the production of refined copper by secondary refiners.
The own price elasticity is broken down into two parts; the first is the positive pure own price effect, and the second is the negative effect on output caused by rising scrap prices due to higher secondary prices. Slade undertakes this measure to account for the close correlation between scrap (input) price and secondary price (output) price. Finally, a scrap stock identity—accounting both for inventories held by scrap dealers and accumulated stock in junk yards—is calculated and incorporated into the model. She then proceeds to estimate the equations. The results indicate that secondary copper price is volatile and magnified by shifts in primary price, and is heavily dependent on economic activity. Moreover, the immediate response of the secondary price is greater than the equilibrium response (that is, secondary price is overly responsive to changed conditions). Slade’s conclusion is that secondary price takes up much of the slack caused by more sluggish primary copper prices. The estimated own-price inelasticity of secondary copper supply is explained by the negative influence of rising scrap prices on the marginal cost of secondary production. Among other inputs the most significant are labor and energy. An increase in the stock of scrap lowers the cost of production and hence is found to positively affect the supply of secondary copper.

**A Model of Secondary Aluminium Pricing**

Based on the reasoning above, fluctuations in the LME primary price is assumed to largely explain fluctuations in the price of secondary aluminium. Since the demand for secondary aluminium is derived from the demand for final goods, a second important determinant of the secondary aluminium price is the activity in the relevant end using sectors. Blomberg and Hellmer (2000) demonstrated the influence on secondary aluminium demand from the automobile sector. However, here we opt for a broader measure of aggregate economic activity to capture the influence form other sectors as well. The following regression equation is proposed:

\[
\ln P_s = \alpha_0 + \alpha_1 \ln P_p + \alpha_2 \ln IP
\]  

where \( P_s \) is the price of secondary aluminium alloys, \( P_p \) is the LME primary price and \( IP \) is an index of industrial production. Equation [1] implies that the entire secondary industry is a price taker. Thus, the price elasticity of industry demand is infinite. This hypothesis may seem unwarranted both because of the relatively separated markets of primary and secondary aluminium, and since the share of secondary aluminium of total European consumption is
approximately one quarter. Such a high share would indicate that the secondary industry should have at least some ‘price power’. However, adopting the reasoning of Slade (1980a), the relevant criterion is not the share of total secondary supply of consumption. Slade argues that the pricing power of the secondary industry is limited by the share of secondary metal produced from old scrap of total consumption. New scrap is ‘uninteresting’ in this context because it is the by-product of manufacturing, thus determined primarily by levels of consumption and not by price. Secondary supply from old scrap on the other hand is sensitive to fluctuations in price. Since no data exist on the tonnage of old and new scrap recovered for Europe, only some very approximate inference on the share of secondary supply from old scrap in Europe could be presented here. Based on the percentage input share of old scrap in German refineries,\(^8\) we conjecture that the share of secondary aluminium supply from old scrap of total consumption is approximately in the 10% range in the four countries included in this study. The small share of aluminium consumption that comes from old scrap is the foundation of our claim that the secondary aluminium industry could, at least within normal output ranges, ignore its influence on secondary price.

\textit{A Model of Secondary Aluminium Supply}

Secondary refiners transform old (\textit{OS}) and new (\textit{NS}) aluminium scrap by the use of a number of inputs, such as capital (\textit{K}), labor (\textit{L}) and energy (\textit{E}). Economic theory stipulates that dual to the production function there exists a cost function that completely describes the production technology (e.g., Varian, 1992). The secondary refiners’ minimum average cost function, \textit{AC}, then depends on the level of output (\textit{Q}) and the prices (\textit{P}_i) of necessary inputs:

\[ AC = f(Q, P_i) \quad i = OS, NS, K, L, E \]

When discussing the cost of producing secondary aluminium it is necessary to examine the effect on cost from the stock of scrap. Increasing secondary production at a certain point in time involves utilizing lower grade and higher cost old scrap, or compete with other users by bidding up price for a fixed supply of new scrap. Marginal and average cost of secondary aluminium production therefore varies with recovery efficiency, defined as the fraction actually recycled of the available stock of old aluminium scrap. Hence, following Slade

\(^8\) Input share data for new and old scrap in secondary refineries exist only for Germany. Since the technology used is similar throughout Europe (i.e. reverberatory furnaces) and the leading price indicator is the LME exchange price, we thus assume that the shares are similar throughout the four countries in this study.
(1980a) we assume the existence of a Cobb-Douglas functional form for the average cost function, so that

\[ AC = a_0 \left( \frac{Q^{\alpha_i}}{SS^{\alpha_i}} \right) \prod P_i^{\alpha_i}, \quad i = OS, NS, K, L, E \]  

where

\[ \alpha, \alpha_0 > 0, \quad 0 < \alpha_i < 1, \quad \sum \alpha_i = 1 \]  

where \( Q \) is secondary aluminium production, \( SS \) is the stock of old scrap, \( Q/SS \) is recovery efficiency and finally \( \alpha_i \) and \( \alpha_2 \) are parameters. The conditions in equation [4] ensure that the cost function [3] is homothetic and hence that a dual production function exist (e.g., Varian, 1992). Equation [3] shows that if secondary production were to increase, cost would go up given the size of the stock. On the other hand, if the stock increased, cost for a given level of secondary production would fall, since refiners now could utilize better quality scrap. Corresponding to the average cost function in [3] are the total cost (\( TC \)) and marginal cost (\( MC \)) functions, so that:

\[ TC = a_0 \left( \frac{Q^{\alpha_i+1}}{SS^{\alpha_i}} \right) \prod P_i^{\alpha_i} \]  

and

\[ MC = \frac{a_0 (\alpha_1 + 1)Q^{\alpha_i}}{SS^{\alpha_i}} \prod P_i^{\alpha_i} \]  

Since we have argued that it is reasonable to assume that the secondary aluminium industry is competitive (see also Blomberg and Hellmer (2000) for further arguments along this line), the \( MC \) curve for the individual producer equals the supply curve of that producer. The horizontal sum of all refiners’ \( MC \) curves constitutes the industry supply curve (see Chambers (1988) for a discussion on the aggregation from firm to industry level). In the neoclassical competitive setting, secondary aluminium output is determined by the intersection between the price and marginal cost schedules in such a way that:

\[ P_s = MC = \frac{a_0 (\alpha_1 + 1)Q^{\alpha_i}}{SS^{\alpha_i}} \prod P_i^{\alpha_i} \]
where $P_s$ is the price of secondary aluminium alloys. To linearize the above expression we take the logarithm of equation [7], which gives:

$$
\ln P_s = \ln[\alpha_0(\alpha_1 + 1)] + \alpha_1 \ln Q - \alpha_2 \ln SS + \sum_{l} \alpha_l \ln P_l
$$

[8]

To get the secondary aluminium supply function, we solve for $\ln Q$ so that:

$$
\ln Q = -\frac{\ln[\alpha_0(\alpha_1 + 1)]}{\alpha_1} + \frac{1}{\alpha_1} \ln P_s + \frac{\alpha_2}{\alpha_1} \ln SS - \sum_{l} \frac{\alpha_l}{\alpha_1} \ln P_l
$$

[9]

Equation [9] forms the basis of the empirical investigation. First, however, we need to construct a measure for the stock of old scrap ($SS$).

A Model of Aluminium Scrap Generation

The stock of scrap is taken here to include not only the inventories of scrap merchants and secondary refiners, but also the aluminium content of scrapped products that over time accumulates in junkyards or elsewhere. For this no data exist. Therefore we need to devise a method to calculate the stock. It should be said right away that the possibility of getting a precise and accurate measure of the scrap stock is bordering the impossible since, as will be made clear, not only will we be forced to make some strong assumptions, but also because of the lack of data for the recovery of aluminium scrap in Europe.

Earlier attempts to calculate and estimate the stock of scrap includes for example Fisher et al. (1972). They assume that the stock of copper scrap is equal to cumulative production, i.e., products are instantaneously available for recovery and recycling. Bonezar and Tilton (1975) discuss at length the process of copper scrap accumulation, but proceed to estimate it as a time trend, which they, however, conclude may very well capture other effects such as technological developments in the refinery sector.

Slade [1980a] also deals with copper scrap accumulation. To calculate the scrap stock she makes the twin assumptions of constant product life times and unchanged composition of the product mix over time. The product mix Slade (arbitrarily) assumes to be that of 1976. She further assumes a base year to get a starting value for the stock. The base year is set (also
arbitrarily) to 1942 and the copper scrap stock that year is assumed to be twice the copper consumption in 1942. She then calculates the net addition to the stock by subtracting secondary copper production from the gross addition to the stock.

Melo’s (1999) study of aluminium scrap generation in Germany applies several different probabilistic representations to the lifetime of end use. This is in contrast to Slade’s assumption of a fixed lifetime. Melo calculates the net stock of aluminium scrap by using figures for the recovery potential in different end use sectors, ranging between 20 to 90 percent for household equipment and transport goods respectively. Melo’s results show a continuous increase in the German aluminium scrap stock, which reaches between 500 to 600 thousand tons by 1997.

The variation in product life time between different end uses, and hence the time it takes before the product is scrapped and the aluminium content is available for recovery, varies between less than a year for packaging up to 30 years or more for aluminium in building components. Life times of products may change over time, affecting the inflow and the size of the pool. Shorter useful lives of, for example cars, speed up the inflow into the scrap stock. However, we hold it likely that only minor variations occur in average lifetimes in different end uses. The growth and the size of the stock are also affected by the changing composition of aluminium consumption. If the share of short-lived products, such as packaging grows, so would the inflow into the stock of scrap. The gross addition in the stock of aluminium scrap can be formulated as:

\[
\Delta S_{ij} = \sum_{x} C_{ij(x-x)} \quad i = 1, \ldots, n
\]

where \( \Delta S_{ij} \) are the gross additions at time \( t \) to the stock of scrap in each country \( j \) and \( C_{ij(x-x)} \) represents the amount of aluminium consumed in end use sector \( i \) in country \( j \), \( t-x \) year ago where \( x \) represents the average lifetime of products in end use sector \( i \). Finally \( n \) is the number of end use sectors.

\[\text{9} \text{ Theoretically, the end of life for a product is when the present value of the stream of benefits derived from the product} \text{ equals its scrap value. Initially, the benefits from the product far outweigh the scrap value, but over time} \text{ the product will deteriorate} \text{ and superior substitutes become available, hence lowering the use value until it} \text{ equals the scrap value, and the product is consequently scrapped.}\]

\[\text{10} \text{ The formulation follows in most respects that of Slade (1980a). However, when doing the actual calculations,} \text{ we do not, like her, assume constant shares of consumption, but instead utilize data on actual shares.}\]
For the net additions to the aluminium scrap stock, we must subtract what is recovered from it every year, i.e., secondary aluminium production. Thus, the size of the aluminium scrap stock in tons can be written as:

\[
SS_j = SS_{j(t-1)} + (\Delta SS_{j(t-1)} - Q_{j(t-1)})
\]

\[
= SS_{j(t-1)} + \sum_{t=1}^{n} (\Delta SS_{j(t-1)} - Q_{j(t-1)})
\]

where \(SS_{j(t)}\) is the stock at some base year \(t_0\) in country \(j\), and \(\Delta SS_{j(t-1)}\) is the net addition to the scrap stock previous year in country \(j\). Finally, \(Q_{j(t-1)}\) is the one period lagged secondary production in country \(j\).

Using data on end use consumption (in tonnage) from Metal Statistics and estimated life times for the different end uses by the EAA (1998), we calculate \(SS\) according to equation [10]. The end use shares are presented for two years in Table 2 together with average lifetime estimates. Again, since no data exist on the tonnage recovery of old scrap for Europe, we approximate this by taking the input share of old scrap in German secondary aluminium refineries and multiplying it with the output of secondary aluminium refiners in Germany, France, Italy and the UK. Leaning on the method used by Slade (1980a), the base year for our calculations was arbitrarily chosen to be 1982, and the initial stock at that date was set to be twice the value of aluminium consumption that year in the respective country (an admittedly low value). The resulting stocks of each country are presented in Figure 3.

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11. Export and imports of aluminium containing products add or subtract to the stock of aluminium scrap, but the size of their impact is extremely difficult to estimate. Direct export and imports of scrap also change the size of the stock. However, trade data for scrap are at best poor. Thus, we have opted to overlook them. The stock that we calculate might therefore for some years be somewhat biased due to this.

12. When doing the actual calculations the Mechanical and Electrical engineering sectors were treated as one single sector. The Chemical engineering and Powder, Iron and Steel and Miscellaneous uses were also grouped together. Finally, the long lag from construction to scrapping for building materials (30 years) implies that figures for the building sector could only be included for the two last years (1996 and 1997) because of lack of end use statistics prior to 1966.

13. This approach can be justified by the fact that most refiners throughout these four countries use similar technologies (i.e., reverberatory furnaces). Furthermore, secondary refiners are the only ones that can handle and refine old scrap of various qualities. One caveat here is the toll remelting of cans by remelters. A substantial part of the packaging sector is made up of cans. Thus, by subtracting only secondary production from secondary refiners - and not take account for the fact that a substantial amount of old used cans go to remelters – the stock might be overestimated. Also price movements of old scrap follow the price of secondary aluminium, and that in its turn, as was discussed above, to a large extent is determined by the LME exchange price. Thus price movements of old aluminium scrap usually follow a similar pattern in the four countries. Of course other factors might make the input shares differ. Finally, this approach assumes that there are no losses when converting old and new scrap into secondary aluminium, which there of course are. However, the effect of this overlook should be small (leading to a slight overestimation of the stock), and is likely not to affect the trend.
Table 2. Average Product Life and Sector Share Consumption of Primary and Secondary Aluminium 1970 and 1996

<table>
<thead>
<tr>
<th>End Use Sector</th>
<th>Germany</th>
<th>France</th>
<th>Italy</th>
<th>United Kingdom</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transport</td>
<td>12</td>
<td>0.273</td>
<td>0.351</td>
<td>0.360</td>
</tr>
<tr>
<td>Mechanical Engineering</td>
<td>10</td>
<td>0.089</td>
<td>0.084</td>
<td>0.078</td>
</tr>
<tr>
<td>Electrical Engineering</td>
<td>10</td>
<td>0.147</td>
<td>0.052</td>
<td>0.141</td>
</tr>
<tr>
<td>Building and Construction</td>
<td>30</td>
<td>0.160</td>
<td>0.201</td>
<td>0.083</td>
</tr>
<tr>
<td>Chemical Engineering</td>
<td>10</td>
<td>0.032</td>
<td>0.008</td>
<td>0.018</td>
</tr>
<tr>
<td>Packaging</td>
<td>1</td>
<td>0.099</td>
<td>0.100</td>
<td>0.097</td>
</tr>
<tr>
<td>Household and Office Applications</td>
<td>5</td>
<td>0.025</td>
<td>0.038</td>
<td>0.053</td>
</tr>
<tr>
<td>Powder using ind., &amp; Iron &amp; Steel Ind., &amp; Misc.Uses</td>
<td>10</td>
<td>0.174</td>
<td>0.096</td>
<td>0.171</td>
</tr>
</tbody>
</table>

Sources: EAA and Metal Statistics.

Figure 3. The Development of the Stock of Old Aluminium Scrap

Compared to Melo’s (1999) estimates for Germany in 1997, our stock is approximately twice as big. This effect is due to the fact that Melo uses estimated figures for potential recovery for each sector, while we use a measure for actual production from old
scrap (however admittedly approximate), which is lower than the figures used by Melo. The rapid growth of the stock, however, is similar to the path identified by Melo. A final caveat is that we have not included any measure of net export of aluminium, aluminium containing products and scrap. However, for the former category no estimates, known to the author, exist, and scrap trade data are notoriously unreliable and hard to find. The likely effect of leaving out net exports is that the stock is underestimated, since the countries in this study are net importers of aluminium and scrap (however they probably are net exporters of aluminium containing products). This, however, should not seriously affect the trend over time. By incorporating the calculated figures for the scrap stock, equation [9] can now be estimated in its full.

The implication of the stock growing at a faster pace than secondary production is, according to equation [9] that the cost of recovery and recycling will tend to reduce over time. As the stock grows, secondary refiners will find it easier to obtain good quality scrap as the scrap boundary moves further and further away from current production. Thus, while the price of old and new scrap has a direct impact on the cost of secondary aluminium production, the stock variable measures an indirect effect on cost from the changing availability of scrap and thereby changing the probability of obtaining wanted quality of scrap.

DATA AND ESTIMATION RESULTS

Data
The data used to estimate the model cover Germany, France, Italy and the UK over the time period 1983 to 1997. All data except the LME primary aluminium price are country specific. Figures for secondary aluminium production are from OEA (1983-1998) annual reports and Metal Statistics (1981, 1992, 1994 and 1998). All aluminium-related prices are also taken from the OEA annual reports. The price for primary aluminum is the LME midday cash price. The price for secondary aluminium is the producer price of copper containing alloys.\(^\text{14}\) Input prices for old and new scrap are represented by the price for old cast scrap and new pure cuttings respectively. To avoid some of the multicollinearity problems evident in Figure 2, a weighted average of the price of old and new scrap is calculated.\(^\text{15}\)

\(^{14}\) Alloy specification may vary between countries. For Germany, France, Italy and the UK the alloys are Leg 226, A-59a3, GD Al Si 8, 5Cu3, 5 Fe and LM24 respectively.

\(^{15}\) The weighted price of scrap, \(PSC\), has been calculated using the scrap intake shares of German refiners (see discussion above). The formula used is \(PSC = \text{Share of old scrap at time } t \times \text{Price of old scrap at time } t \) + Share
All aluminium prices are measured in US ct/lb. Labor costs for Germany and the UK are taken from International Labor Statistics (ILO), and are measured as the hourly wage rate in the local currency for workers in the non-ferrous metal basic industries (ISIC-code 372). For France labor costs are from Eurostat and measure hourly wage rates in the basic metal industry. For Italy, only an hourly compensation index for industrial workers was accessible from the Bureau of Labor Statistics. All wage costs have been transformed to US$. Energy costs are represented by the industry price for heavy fuel oil in US$/ton taken from the IEA statistics. All prices have been deflated with the World Bank G-7 deflator using 1980 as the base year. To approximate the cost of capital, we have taken the yield of Government Bonds (percent per annum), less annual inflation (percent per annum), as found in the International Financial Statistics (IMF, 1989, 1995 and 1999). As a measure of economic activity the seasonally adjusted Industrial Production Index from the IMF was used.

***Estimation Method and Results***

Before turning to the estimation results, we must comment on the estimation method and the error structure. Equation [1] and [9] will be estimated by pooling data for Germany, France, Italy and the UK for the years 1983-97. In total we then have 60 observations. To enable pooled estimation, the stochastic framework and specification should preferably account for all variables not observed by us, and still let them enter each country’s cost minimizing behavior (Söderholm, 1999). One common approach allowing for this is the so-called fixed effects model. The fixed effect model assumes that any differences across countries can be captured in differences in the intercept term for each country. Such differences will be captured by the use of an additive disturbance term \( (u_{it}) \) (where \( i \) and \( t \) denotes country and time). This disturbance could further be decomposed into two parts so that

\[
 u_{it} = \mu_i + \varphi_{it} \tag{12}
\]

where \( \mu_i \) accounts for the unobservable time invariant country specific error not included in the model, while \( \varphi_{it} \) varies with both time and country and could thus be regarded as the “traditional” error term. The country specific error (\( \mu_i \)) may be interpreted as any unobserved fundamental differences among the different countries’ secondary aluminium supply or

of new scrap at time \( t \) * Price of new scrap at time \( t \). By doing this, we implicitly assume that the mix of old and new scrap, and hence also the technologies in France, Italy and the UK are similar to that in Germany.
pricing. By assuming that these disturbances are fixed over time, we are able to eliminate them by introducing a dummy variable for each country. Thus, the following terms are appended to equations [1] and [9].

\[ \sum_{n=1}^{N} y_n D_n \quad \text{where} \quad D_n = 1 \text{ for country } n \text{ and } 0 \text{ otherwise} \quad [13] \]

The price equation [1]) is estimated by Ordinary Least Squares technique. The supply equation [9]) indicates simultaneity. The quantity supplied to the market is determined jointly by the decision of the producer and the market demand. Therefore, ordinary least square (OLS) estimated parameters of equation [9] would be biased and inconsistent, and the statistical tests invalid (see for example Greene, 1997). Hence, we apply the so-called Two Stage Least Square (TSLS) regression technique to account for the endogeneity of the price of secondary aluminium (see for example Kennedy (1992) for more on the TSLS technique). The estimated results for equations [1] and [9] are shown in Tables 3 and 4.

For the regression of equation [1] (secondary aluminium price determination), the signs are as expected. The LME primary price is a significant determinant of the secondary aluminium price. When the LME primary price \((Pp)\) increases by one percent, the producer price for secondary aluminium increases by 0.76 percent. The inelastic response of the secondary price, however, gives some weight to the claim that secondary aluminium only competes with the primary material in the cast market. In other words, increased demand for primary aluminum increases the primary price, leading foundries to replace primary by secondary in the production of castings to an even greater extent, thereby driving up the secondary price. In the wrought market, however, there are only limited possibilities to substitute secondary for primary; hence the inelastic response of the secondary aluminium price. As expected, an increase in economic activity \((IP)\) influences the price of secondary aluminium through increased demand for secondary aluminium alloys by auto manufacturers and others. However, the effect on price is relatively modest. A one percent increase in industrial activity leads to a 0.47 percent increase in the secondary price.
### Table 3. OLS Estimated Results for the Price Equation (equation [1])

<table>
<thead>
<tr>
<th>Variable</th>
<th>Est. Elasticities</th>
<th>t-statistics</th>
<th>Country specific statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td>LME Primary Price</td>
<td>0.76*</td>
<td>17.3</td>
<td></td>
</tr>
<tr>
<td>Industrial Production</td>
<td>0.47*</td>
<td>2.9</td>
<td>Germany 0.92 2.11</td>
</tr>
<tr>
<td>Intercept Dummy Germany</td>
<td>-1.08</td>
<td>-1.4</td>
<td>France 0.75 1.24</td>
</tr>
<tr>
<td>Intercept Dummy France</td>
<td>-0.98</td>
<td>-1.3</td>
<td>Italy 0.88 1.26</td>
</tr>
<tr>
<td>Intercept Dummy Italy</td>
<td>-1.12</td>
<td>-1.5</td>
<td>United Kingdom 0.70 1.81</td>
</tr>
<tr>
<td>Intercept Dummy UK</td>
<td>-1.18</td>
<td>-1.6</td>
<td></td>
</tr>
</tbody>
</table>

*Statistically different from zero at the 5 percent level.

### Table 4. TSLS Estimated Results for the Supply Equation (equation [9])

<table>
<thead>
<tr>
<th>Variable</th>
<th>Est. Elasticities</th>
<th>t-statistics</th>
<th>Country specific statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Price Secondary Aluminium</td>
<td>0.78*</td>
<td>3.2</td>
<td></td>
</tr>
<tr>
<td>Price Scrap</td>
<td>-0.43*</td>
<td>-2.5</td>
<td>Germany 0.29 2.12</td>
</tr>
<tr>
<td>Price Labor</td>
<td>-0.23*</td>
<td>-2.4</td>
<td>France 0.51 1.40</td>
</tr>
<tr>
<td>Price Capital</td>
<td>-0.003</td>
<td>-0.1</td>
<td>Italy 0.46 1.92</td>
</tr>
<tr>
<td>Price Energy</td>
<td>-0.22*</td>
<td>-2.5</td>
<td>United Kingdom 0.09 1.06</td>
</tr>
<tr>
<td>Scrap Stock</td>
<td>0.07*</td>
<td>3.1</td>
<td></td>
</tr>
<tr>
<td>Intercept Dummy Germany</td>
<td>11.89*</td>
<td>13.6</td>
<td></td>
</tr>
<tr>
<td>Intercept Dummy France</td>
<td>13.06*</td>
<td>14.3</td>
<td></td>
</tr>
<tr>
<td>Intercept Dummy Italy</td>
<td>12.46*</td>
<td>11.6</td>
<td></td>
</tr>
<tr>
<td>Intercept Dummy UK</td>
<td>13.03*</td>
<td>14.9</td>
<td></td>
</tr>
</tbody>
</table>

*Statistically different from zero at the 5 percent level.

All estimated coefficients of the supply equation have the expected signs, and with the exception of the coefficient for the capital variable, are significant at the five percent level. The supply of secondary aluminium is price inelastic, a one percent increase in the own price increases supply by 0.78 percent, a still quite significant response. Blomberg and Hellmer (2000), for example, estimate an own price response of 0.17 percent. Since scrap purchases represent the bulk of the costs, the significant effect on supply (-0.43 percent) of changes in
scrap prices is to be expected. However, before we interpret the other coefficients and draw conclusions about this market, we should pause and reflect upon one specific characteristic of secondary production and supply and its ramifications.

We can note from Figure 2 that the principal input prices, the price of old and new scrap are closely correlated with the output price \( P_s \). Correlation coefficients for the different countries are presented in Table 5.

**Table 5. Correlation Between Input and Output Prices in the Secondary Aluminium Market**

<table>
<thead>
<tr>
<th></th>
<th>Germany</th>
<th>France</th>
<th>Italy</th>
<th>United Kingdom</th>
</tr>
</thead>
<tbody>
<tr>
<td>Price Secondary Alum. Alloy – Price of Old Scrap</td>
<td>0.957</td>
<td>0.880</td>
<td>0.965</td>
<td>0.869</td>
</tr>
<tr>
<td>Price Secondary Alum. Alloy – Price of New Scrap</td>
<td>0.956</td>
<td>0.821</td>
<td>0.945</td>
<td>0.782</td>
</tr>
</tbody>
</table>

The high correlation found between input and output prices means that any increase in the secondary alloy price leads to an almost instantaneous increase in the scrap price. In other words, the two independent variables are not independent. Figure 4 further illustrates the process. If we assume that the price of secondary aluminium alloys increases from, say, \( P_0 \) to \( P_1 \), ceteris paribus, output would increase from \( Q_0 \) to \( Q_1 \). However, since a rise in secondary price will make scrap prices increase as well, the costs of production will go up and the \( MC \) curve will shift from \( MC_0 \) to \( MC_1 \) and hence, the production increase will only be \( Q_1' \). The effect of price changes in the secondary alloy market will thus only give rise to minor changes in output and hence the amount of aluminium recycled. In fact, there exist a slight possibility that if the price of scrap is extremely sensitive to changes in the secondary price - that is a rise in the secondary price makes the scrap price increase even more than the output price – the net effect (net elasticity) on output might be negative. This is exemplified by the shift of the \( MC \) curve to \( MC_2 \) and the corresponding output level \( Q_1'' \).

Because of the dependence between the input and output prices, the output price elasticity estimated by using equation [9] is likely to be “too large”, and a revised supply function could be devised.
AN ALTERNATIVE SUPPLY FUNCTION

If changes in the output price of secondary aluminium ($P_s$) give rise to an almost identical change in the weighted input price of old and new scrap ($P_{sc}$), we can assume that

$$\ln P_{sc} = \lambda \ln P_s$$  \hspace{1cm} [14]

where $\lambda$ is some factor measuring the sensitivity of scrap prices to changes in secondary aluminium alloy prices ($\lambda$ is thus a constant). Substituting $\lambda \ln P_s$ for $P_{sc}$ in equation [9] we get

$$\ln Q = -\frac{\ln[a_0(a_1+1)]}{a_1} + \frac{1}{a_1} \ln P_s + \frac{\alpha_2}{a_1} \ln SS - \sum \frac{\alpha_i}{a_1} \ln P_i - \frac{\lambda \alpha_1}{a_1} \ln P_s$$  \hspace{1cm} [15]

or

$$\ln Q = -\frac{\ln[a_0(a_1+1)]}{a_1} + \frac{1}{a_1} (1 - \lambda \alpha_3) \ln P_s + \frac{\alpha_2}{a_1} \ln SS - \frac{1}{a_1} \sum \frac{\alpha_i}{a_1} \ln P_i$$  \hspace{1cm} [16]

$$i = K, L, E$$
In equation [16] the output price elasticity is $1/\alpha_1(1 - \lambda \alpha_s)$. According to Slade (1980a), this elasticity could be interpreted as follows. The first part, $1/\alpha_1$, is the partial output price elasticity we obtain if we hold all input prices constant. Hence, $\alpha_1$ determines the slope of the MC curve in Figure 4. The second part, $-\lambda \alpha_s/\alpha_1$, shows the decrease in output due to the increase in the scrap prices. Hence, $-\lambda \alpha_s/\alpha_1$, shifts the MC schedule in Figure 4 from $MC_0$ to $MC_1$. The size of the shift depends on $\alpha_s$, the cost share of scrap in secondary aluminium production, $\lambda$, the sensitivity measure of scrap prices to changes in secondary prices, and $\alpha_1$, the output elasticity of marginal cost. Thus, returning to Figure 4, even if the partial output elasticity $1/\alpha_1$ might be high (the shift from $Q_0$ to $Q_1$) the net effect taking account of the simultaneous increase in scrap prices $-\lambda \alpha_s/\alpha_1$, diminishes the increase in production to $Q_1'$. We now proceed to the estimation of equation [16].

*Estimation Results II*

Estimation results of equation [16] are presented in Table 6. The equation was estimated by the same data and methods used to estimate equation [9].

<table>
<thead>
<tr>
<th>Variable</th>
<th>Est. Elasticities</th>
<th>t-statistics</th>
<th>Country specific statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Price Secondary</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminium</td>
<td>0.21*</td>
<td>2.4</td>
<td>Adj. R² D-W statistic</td>
</tr>
<tr>
<td>Price Labor</td>
<td>-0.15</td>
<td>-1.6</td>
<td>Germany 0.35 1.21</td>
</tr>
<tr>
<td>Price Capital</td>
<td>0.01</td>
<td>0.6</td>
<td>France 0.37 1.21</td>
</tr>
<tr>
<td>Price Energy</td>
<td>-0.25*</td>
<td>-2.9</td>
<td>Italy 0.62 2.07</td>
</tr>
<tr>
<td>Scrap Stock</td>
<td>0.07*</td>
<td>3.2</td>
<td>United Kingdom 0.31 0.82</td>
</tr>
<tr>
<td>Intercept Dummy Germany ($\gamma_g$)</td>
<td>12.62*</td>
<td>15.4</td>
<td></td>
</tr>
<tr>
<td>Intercept Dummy France ($\gamma_f$)</td>
<td>13.93*</td>
<td>16.6</td>
<td></td>
</tr>
<tr>
<td>Intercept Dummy Italy ($\gamma_i$)</td>
<td>13.69*</td>
<td>14.4</td>
<td></td>
</tr>
<tr>
<td>Intercept Dummy UK ($\gamma_{UK}$)</td>
<td>13.79*</td>
<td>16.9</td>
<td></td>
</tr>
</tbody>
</table>

*Statistically significant at the 5 percent level.

16 The cost share of scrap accounts for something between 60-70 percent of variable costs (personal communications with representatives of Gotthard Aluminium, Sweden, 1999).
As expected, the output price elasticity estimated from equation [16] is lower than the one from equation [9]. A one percent increase in secondary price now only leads to a 0.21 percent increase in secondary supply, the explanation being that when secondary price goes up, so does the price of the most important input, scrap.

The low own price elasticity indicates that price driven policies to stimulate aluminium recycling would potentially be ineffective. For example, assume a per unit subsidy for secondary aluminium production of 20 US cents per pound. This means that the price received by the secondary refiner will be raised by 20 cents. If we assume that the price the foundries (the consumer) pay is left unaffected, consumption will not change. Such a subsidy corresponds to a 19 percent price increase if we use the average nominal 1997 January prices in the four countries studied here. With the estimated price elasticity such price increase will increase secondary supply by approximately 4 percent (0.21*0.19), which in turn corresponds to a mere one percent unit increase in the market share of secondary aluminium alloys. The infectiveness of such policies found here corresponds to, for example, Slade’s (1980a) simulations of subsidies to secondary copper producers in the US. Thus, if increased aluminium recycling is desired, per unit subsidies might not be the most effective way to go about it.

The effects on the coefficient estimates of the other variables are small. However, the coefficient for the cost of labor is now statistically insignificant. The coefficient for capital is still statistically insignificant and now has the wrong sign. In both estimations (equations [9] and [16]) the coefficient of capital gets a low value. The barely measurable effect on secondary production from changes in capital price could have two causes. First, secondary production is far less capital intensive than is primary production. Thus, it should be less sensitive to changes in capital costs. Second, our price of capital, real government bond yield, is at best an approximation of the true capital cost. Secondary aluminum production is far less energy intensive than is primary production (down to five percent of the energy requirement of primary smelting). Still, a one percent increase in energy costs make secondary supply decrease by 0.25 percent.

17 We simply increase the production of secondary aluminium in 1997 by a factor of 1.04, and then divide this new production figure by total aluminium consumption in the four countries included in this study.

18 The calculations should be viewed as nothing more than a simple exemplification. The simulation is static in the sense that we have not considered the effect of the subsidy might have in a broader perspective. Also, when calculating the increase in market share, we use total consumption as the base, thus neglecting the fact that secondary aluminium competes with primary aluminium only in the cast market.
While the price of scrap has a direct impact on the cost of secondary aluminium production, the stock variable measures an indirect effect on cost from the changing availability of scrap and thereby changing probability of obtaining the wanted quality of scrap. As the scrap stock grows over time, it should become less costly (including all cost, such as search- and quality control costs etc) for the secondary refiners to acquire scrap of the required quality as the availability grows. The effect, however, is small. A one percent increase in the stock, ceteris paribus, increases supply by a mere 0.07 percent. The small effect could partly be explained by the fact that a large portion of the scrap recovered and recycled is likely to come from the flow of scrap. This means that most retired products are either recycled ‘immediately’ or ‘forgotten’ in a deposit, where they could be retrieved only at a high cost. The growing stock of aluminium scrap would thus contribute only at the margin to the supply of secondary aluminium.

Comparison with Other Studies

How do our results compare with other studies? Table 7 summarizes supply elasticities from a selection of other studies of metal recycling. The two most interesting results to compare are the own price effect and the effect from the stock of scrap. Comparing the own price estimates in the present paper (equation [16]) with the ones generated in Slade’s studies - who uses the same methodological approach as we do here - on copper (1980a) and copper and aluminium (1980b), we find that they are in the same range (0.20-0.30 percent).

Considering the effect on secondary supply from changes in the size of the stock of metal scrap, our estimates are substantially lower than Slade’s, with the exception of her 1980b study of copper recycling. For example, in her study of aluminium recycling in the US, a one percent increase in the stock increases, ceteris paribus, secondary production by 1.3 percent, compared to only 0.07 percent in the present study. The cause of this discrepancy could only be speculated on, but might have to do with the different time period and regions used. Slade uses data covering the 1950s up to the middle of the 1970s. During this time, the absolute size of the stock should have been considerably lower in absolute terms than the stock we have today (with ongoing accumulation). Thus the effect from the growing stock might have been more sizable at the time she was doing her estimations. Finally, considering

19 See Tilton (1985) for reasoning along these lines.
20 The reader should be forewarned that the elasticities presented in Table 7 results from different estimation techniques, using different data for other periods than the ones we use. Furthermore, even though copper and aluminium share many similarities they are still traded in different markets that in turn differ in their institutional set up. Hence, any comparison should be made with outmost carefulness.

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input costs other than scrap, all studies presented here indicates that secondary metal production is more sensitive to changes in input costs than do our results. The cause of this is in most cases explained by the fact that they include fewer inputs. Blomberg and Hellmer (2000) include only labor, Carlsen (1980) have only fuel and Slade (1980a, 1980b) estimates the effect from energy and capital prices. The variables included in these studies will thus capture some of the effect from omitted variables.

Table 7. Comparison of Supply Elasticities from Selected Studies and the Ones Estimated in the Present Study

<table>
<thead>
<tr>
<th>Study</th>
<th>Price Secondary Metal</th>
<th>Price Scrap</th>
<th>Price Other Inputs</th>
<th>Scrap Stock</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present Study</td>
<td>0.78 (Eq.9)</td>
<td>-0.43 (Eq.9)</td>
<td>-0.15 (labor)</td>
<td>0.07 (Eq.16)</td>
</tr>
<tr>
<td></td>
<td>0.21 (Eq.16)</td>
<td></td>
<td>0.01 (capital)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-0.25 (energy)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(All from Eq.16)</td>
<td></td>
</tr>
<tr>
<td>Blomberg &amp; Hellmer (2000)</td>
<td>0.17</td>
<td>-0.10 (Weighted av. new &amp; old scrap)</td>
<td>-0.24 (labor)</td>
<td></td>
</tr>
<tr>
<td>(Aluminium)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carlson (1980) (Aluminium)</td>
<td>0.32</td>
<td></td>
<td>-0.88 (fuel)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.69 (fuel lagged one year)</td>
<td></td>
</tr>
<tr>
<td>Slade (1980a) (Copper)</td>
<td>0.28</td>
<td></td>
<td>-0.23 (capital)</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-0.33 (labor)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-0.49 (energy)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-0.11 (chemicals)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-0.07 (transport)</td>
<td></td>
</tr>
<tr>
<td>Slade (1980b) (Aluminium)</td>
<td>0.24</td>
<td></td>
<td>0.47 (energy)</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-0.99 (capital)</td>
<td></td>
</tr>
<tr>
<td>Slade (1980b) (Copper)</td>
<td>0.29</td>
<td></td>
<td>-0.47 (energy)</td>
<td>0.11</td>
</tr>
</tbody>
</table>

CONCLUSIONS

The purpose of this study has been to identify the fundamental economic factors behind the recovery and recycling of aluminium scrap into ‘new’ aluminium metal. Models for the pricing and supply of secondary aluminium were estimated for Germany, France, Italy and the UK for the years 1983-97.

Considering first the pricing in the secondary market, we estimate a model where we assume that the secondary aluminium industry as a whole is a price taker, with the primary industry ‘dictating’ the secondary price through the LME primary price. The results show that a one percent increase in the LME primary price increases the secondary alloy price by 0.76
percent. The inelastic response indicates that secondary aluminium cannot completely fill the slack caused by variation in the primary price in the aluminium market as a whole, and supports our proposition of partly separate markets for primary and secondary aluminium. If primary price increases, foundries are induced to replace primary for secondary, thereby driving up secondary aluminum price. However, this process stops short of a one-to-one relationship since substitution between primary and secondary aluminium can only take place - at least to any significant degree - in the market for casting alloys.

Second, we estimate two versions of secondary aluminium supply. The first variant explicitly includes the scrap price. However, examining the output price and the scrap price reveals that they are closely correlated. When the price of secondary aluminium alloys increases, so will, almost instantaneously, the price of scrap, increasing production cost and thus, diminishes the supply increase. The effect of this is that the inclusion of scrap prices in the estimation would make us overestimate the supply response of the secondary aluminium industry. Thus, we estimate an alternative version accounting for this effect. The own price elasticity of supply of secondary aluminium is significantly reduced. A one percent increase in the price of secondary aluminium alloys now induces a 0.21 percent increase in secondary supply, which is in line with previous research of metal recycling markets. This indicates that price driven policies to stimulate aluminium recycling would potentially be ineffective. A simple static calculation shows that a 20 US cent per unit subsidy to the secondary refineries, corresponding to a 19 percent price increase in the price they receive, would make the market share of secondary aluminium increase a mere one percent.

Moreover, the secondary aluminium industry is not especially sensitive to changes in other input costs apart from scrap. This result is not surprising. Old and new scrap dominate the structure of total cost of secondary output, and constitute between 60-70 percent of variable costs at the average refiner. Thus, all other costs should have lesser impacts. Only energy (heavy fuel oil) appears to be of importance according to our estimates.

While the price of scrap has a direct impact on the cost of secondary aluminium production, the scrap stock variable measures an indirect effect on cost from the changing availability of scrap and thereby changing probability of obtaining the wanted quality of scrap. A rough calculation of the scrap stocks in the four countries included in the study is made, and it indicates a steady growth in the stock. As the stock grows and availability increases, cost for recovery and recycling will, theoretically, go down. Our estimate indicates a statistically significant, yet modest effect of the growth in the stock. A one percent increase in the stock increases secondary supply by only 0.07 percent through cost savings.
The inelastic response is probably explained by the fact that most recycled scrap comes from the flow of scrap, and not from the stock (what is not recycled immediately after retirement is not very likely to ever be recycled, probably due to prohibitive cost of searching, quality control etc.). However, as historical data for the actual amount of scrap produced, the age of products when retired and the share of scrap that is actually recovered from the scrap stream are lacking, our calculation of the size of the aluminium scrap stock provides us at best with a rough figure. Thus, our estimations of the impact on the supply of secondary aluminium from the stock of scrap must be read carefully. It also points to the need for developing better measures of the factors mentioned above, to provide for better estimates, and thus, better planning tools for the secondary industry and public officials dealing with recycling.

Our final remark is that the market for aluminium made from scrap indeed basically behaves like economists would expect, with supply reacting to economic stimuli etc. Whether there is enough aluminium recycling done or not, i.e., if the amount recycled is socially optimal, is however another question. Given the fact that increased aluminium recycling probably must come from the stock, and given the low elasticity of the scrap stock we have found, it is, however, our tentative conclusion that policies aimed at increasing recycling could be costly.

REFERENCES


