University of Alberta

Environmentally Sensitive Analysis of Economic Performance: Productivity and Efficiency in the Canadian Pulp and Paper Industry, 1959-1994

by

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Abstract

Most empirical studies of productivity to date have considered only marketed or desirable outputs and have neglected changes in the production of pollutant outputs. This neglect of negative externalities is also evident in studies that have attempted to assess the impact of environmental regulation on productivity growth. A redefinition of technologies to provide a more correct representation of the production process is needed to get a less distorted measure of economic progress.

This thesis reports the results of three studies analyzing productivity trends in the Canadian pulp and paper industry from 1959 to 1994. First, input distance function as well as index number approaches are employed to analyze productivity and efficiency changes in the industry without the incorporation of undesirable outputs. The results from the Tornqvist index number analysis indicate that the average annual total factor productivity (TFP) growth rate due to technological progress and efficiency change was -0.06%. Based on the input distance function estimation, the average annual rate of productivity growth was estimated to be 0.19%. Almost all of this productivity growth in the industry was due to technical change.

In the second study, changes in the industry's two major water pollutant outputs, biological oxygen demand (BOD) and total suspended solids (TSS), are incorporated into the distance function analysis. The average rate of TFP growth was estimated to be 1.00% per year, considerably higher than the estimate obtained without considering pollutant outputs.

The third study employs primal and profit dual nonparametric techniques to conduct productivity analysis in environmentally sensitive ways. The nonparametric analyses results confirm those obtained from the input distance function analyses. Our pollutant shadow price or pollution abatement cost estimates, however, indicate that the cost to producers of pollution control has been rising. The main conclusion from the three studies is that productivity improvement, from the social viewpoint, has been more successful than conventional productivity measures would suggest.

Dedicated to
my parents, Hailu and Selas,
and my wife, Haregu Ambaye

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CHAPTER 1 Introduction and Statement of Research Problem

Most of the work on efficiency and productivity growth to date has considered only marketed or desirable outputs and has ignored changes in the environmental effects of economic activity. This bias is also evident in studies that have attempted to assess the impact of environmental regulation by counting the costs of environmental protection while at the same time ignoring the benefits of protecting the environment. A redefinition of technologies and productivity measures to provide a more accurate representation of the production process and the choices that societies face is needed to get a less distorted measure of economic progress and to guide policy accordingly.

This study explores alternative approaches to the measurement and analysis of economic performance in environmentally sensitive ways using data from the Canadian pulp and paper industry for the period from 1959 to 1994. Pulp and paper is Canada's largest manufacturing industry measured in terms of employment, value added and net exports (CPPA 1996b). This industry is the world's largest market pulp supplier, accounting for more than 25 percent of world supply of market pulp. Canada is also the largest producer and exporter of newsprint in the world; more than 25 percent of the world's newspaper printing uses Canadian paper.

The industry is also a significant source of water pollution, accounting for about 50 percent of all the waste dumped into the nation's waters (Sinclair 1990). Recently, the pulp and paper industry has been the focus of considerable attention from the public as well as from provincial and federal regulatory agencies because of its environmental effects. This study analyzes productivity growth in the industry by taking into account the way the industry has treated the environment.

1.1 The Background

Speaking broadly and informally, productivity is about how much we get in products or services out of the resources we use. Productivity is one of the major things that economics is fundamentally about, whether the economizing is from the point of view of an individual, a firm, an industry, a nation, or the global economy as a whole. At the firm and industry levels productivity determines competitiveness and profitability. At the national and global levels, productivity is one of the most important determinants of standards of living.

What appear to be small changes in productivity growth rates may compound over time to cause serious economic consequences. For example, growing at the 1960-80 average percentage rate of 3.32, Canadian GDP per capita would double every 22 years. But it would take it 82 years to double if it grew at the 1980-94 average rate of 0.86 percent.[1] Faster productivity growth makes it easier to deal with problems of poverty, income distribution and the provision of public goods. Thus there is no wonder that changes in productivity growth attract serious attention from economists, politicians, the business community and others.

This is especially true of the slowdown in productivity growth of the industrialized nations that began in the late 1960s or early 1970s. The average GNP per capita growth rate for the seven major OECD countries (Canada, France, Germany, Italy, Japan, United Kingdom and the United States) declined from 4.3 percent for the 1955 –73 period to only 1.9 percent for the 1973-1986 period.[2] This slowdown has been called the most significant macroeconomic development of the last two decades (Fischer 1988).

Although there is no universal agreement among economists, several potential causes for the observed productivity slowdown have been identified including: the OPEC energy price increase of 1973 and 1979, possible decline in the skills of labour,[3] and additional costs imposed by environmental regulations that have been enacted beginning in the 1970s.[4] The search is far from over. In particular, the impact of environmental regulations is the subject of ongoing research and debate between those who have recently argued that environmental regulations can improve economic performance and those holding the traditional view that these regulations retard productivity growth.

Proponents of the traditional view that regulation retards productivity growth point to the empirical evidence in the literature accumulated over the period of the last 20 years. Based on their survey of empirical studies on the subject, Jaffe *et al* (1995) find that estimates indicate that environmental regulation has reduced productivity growth by 8 to 16 percent in the case of US manufacturing. Other studies have indicated that productivity losses were larger in more heavily regulated sectors, such as the US electric utilities industry (see Repetto *et al* 1996).

In a recent study of the paper industry and four other heavily regulated US manufacturing industries, Barbera and McConnell (1990) conclude that 10 to 30 percent of the decline in productivity from the 1960s to the 1970s is attributable to direct abatement capital expenditure and the indirect effects of environmental regulation on production processes. The effects were highest in the case of the paper industry where abatement accounted for 30percent of the reduction in productivity.

In another study covering the US pulp and paper industry, Gray and Shadbegian (1995) use plant level data for the period from 1979 to 1990 to study the connection between productivity and pollution abatement. They find that abatement costs have significant effects on plant productivity levels, a $1 extra cost in abatement having the equivalent of $1.74 loss in productivity.[5]

The traditional view is challenged by those who hold that environmental regulations can improve, rather than reduce, productivity and competitiveness (Porter 1991; Porter and van der Linde 1995). According to this view, also known as the "Porter hypothesis", the traditional belief that environmental regulation retards productivity grows out of a static view in which information is perfect and firms have already discovered all profitable opportunities for innovation. Porter and van der Linde argue that a better view of reality is one where there are technological opportunities that remain unexploited because of the incomplete nature of the information that firms have, as well as organizational inertia and problems of aligning individual, group and corporate incentives.

Under such circumstances, the proponents of the Porter hypothesis argue that properly designed and strict environmental regulations can trigger product or process innovations that "partially or more than fully offset" the private costs of complying with these regulations. They further argue that a nation may also benefit from early-mover advantages by imposing strict environmental regulations early, in order to enhance competitiveness. Porter and van der Linde provide many examples from case studies where such "offsets" have been observed and argue that "innovation offsets to environmental regulation are common." They also point out that studies have found little evidence that supports the common claim that environmental regulations (in the US) adversely affected its competitiveness.[6]

There is little disagreement about the appropriateness of many of the policy prescriptions deriving from the Porter Hypothesis. For example, the innovation fostering advantages of incentive-based environmental regulations over command-and-control approaches are widely recognized and accepted among economists. There is also little disagreement about the usefulness of information in the dissemination of new environmental technologies. In the presence of unexploited or overlooked opportunities, environmental regulations may spur innovations that could offset associated cost.

Nonetheless the central claim of the hypothesis, that innovation offsets are significant and pervasive, has attracted criticism. For examples of this criticism, see Palmer, Oats and Portney 1995. Data collected by the Bureau of Economic Analysis for the US indicate that cost offsets amount to less than 2 percent of environmental expenditures, hardly big enough to support the Porter-van der Linde hypothesis.

Cost offsets also have little to do with the absence of significant evidence of adverse effects of environmental regulations on competitiveness. Jaffe *et al* (1995) forward other possible reasons for the absence of such effects. Compliance costs constitute a small percentage of production costs; differences in the environmental regulations in different industrialized nations are too small; and firms prefer to build state-of-the-art facilities even in developing countries where environmental standards are currently lax. Moreover, different studies have employed different measures of competitiveness. Not all the measures employed are idea.

Unfortunately, the approaches followed by proponents of the two views on the environment-productivity debate have important shortcomings. In particular, both sides treat the environment as 'external' and fail to consider the social benefits of environmental protection. For environmental regulations to be worthwhile, it is not necessary that innovation or cost offsets be more than compliance costs. It is enough that the regulations pass the test of social benefit-cost analysis; and the social benefits of pollution reduction or environmental improvement that are completely ignored in the Porter hypothesis are an integral part of the benefit-cost analysis.

Similarly, those with the traditional view of trade-offs between the environment and productivity employ conventional measures of economic performance, ignoring the benefits of environmental improvement, while at the same time counting in capital and other input costs of pollution abatement. As a result, they inevitably draw the same conclusion: environmental regulation causes productivity losses. Thus, like the Porter hypothesis, this methodologically flawed empirical evidence has the potential to cause misunderstandings and distortions in the policy making process.

1.2 Objectives of this Study

The discussion above about the controversy surrounding productivity and environmental regulation highlights the importance of taking account of environmental effects in the analysis of economic performance. A more appropriate way to measure economic progress in general, and to frame the environment-economic performance issue in particular, is to define economic performance to include the social benefits associated with environmental regulation or abatement and ask what has been happening to productivity, as measured in environmentally sensitive ways. Such an approach would provide a more accurate view of economic progress and social welfare. This requires the use of more complete representations of production technologies that allow us to incorporate both the private and social costs and benefits of productive activity.

A major focus of this study is to use such an approach to assess the performance of the Canadian pulp and paper industry in the period from 1959 to 1994. This is accomplished using alternative approaches for modelling the production technology. First, the structure of the industry's production technology is explored using input distance functions estimated without undesirable outputs. The results from input distance functions are compared to similar results derived from index number analysis.

Second, the environmental effects of the industry are brought into the analysis by specifying and estimating parametric input distance functions incorporating two major water pollutant outputs of the industry, along with marketed inputs and outputs. Four desirable outputs, two major water pollutant outputs (BOD and TSS),[7] and seven inputs were identified in the estimation of input distance functions. Estimates of producer abatement costs or pollutant shadow prices are also derived based on the estimated input distance functions.

Third, nonparametric approaches for modelling production technologies with and without undesirable outputs are explored. The nonparametric methods allow us to build inner and outer bounds to the underlying production technology without imposing restrictive functional forms.

1.3 Organization of the Study

This study has five chapters in total. The remainder of this introductory chapter is devoted to general discussion about the Canadian pulp and paper industry: its significance in the national economy, the nature of the pulp and paper making process and related environmental effects. Pollution abatement activities in the industry are also described later in this chapter. The chapter closes with a description of the nature and sources of the data used in the study.

In the second chapter, results from two different approaches to productivity measures, as conventionally defined, are examined. Index numbers are used to study both single factor and total factor productivity (TFP) trends in the industry. Adjustments for output scale effects are then made on the Tornqvist TFP estimates to derive input-based Malmquist indexes that measure changes in productive efficiency and technical change. These results are discussed and compared to those obtained from an input distance function analysis, the second approach explored in the study.

The impact of accounting for environmental effects is explored using input distance functions with pollutant outputs in the third chapter. The use of input distance functions provides a framework for analyzing productivity growth and other parameters of a multi-output technology without the need for external pollution damage estimates. In fact, it also provides a framework from which pollutant shadow prices can be estimated.

The comparison between conventional and environmentally sensitive measures is continued in the fourth chapter, using nonparametric techniques. New and simple approaches for incorporating environmental effects in primal and profit-dual nonparametric approaches are proposed and implemented. The nonparametric technology bounds are formulated in effective quantities to incorporate technological change into the analysis. Both intertemporal and effective quantity nonparametric approaches are employed for this purpose.

The fifth chapter summarizes and compares the findings from the different studies. The implications of these findings as well as suggestions for further research work are discussed in that chapter.

1.4 The Pulp and Paper Industry in Canada

1.4.1 National Significance

Pulp and paper is Canada's largest manufacturing industry measured in terms of employment, value added and net exports (CPPA 1996b, p. 5). In 1995, the pulp and paper industry was the source of direct employment for 66,000 people, which amounts to about 0.5percent of total employment in the Canadian economy. The industry produced 28.8 million tonnes of pulp and paper in 1995. Out of this, the industry exported 23.6 million tonnes of pulp and paper valued at $25.4 billion. In the period from 1990 to 1995, pulp and paper was the industry that contributed the most to Canada's merchandise trade balance, $86.6 billion, higher than the contribution by energy ($72 billion), mining ($58.8 billion), forest industries other than pulp and paper ($52.3 billion), the auto, trucks and parts industry ($39.9 billion) or fisheries ($10.5).[8]

Not only is the pulp and paper industry the nation's leading manufacturer in terms of production, employment, and net exports, it also is a national industry in the sense that it is a geographically dispersed industrial employer. The 162 mills that comprised the industry in 1994 were located in Quebec (67), Ontario (34), British Colombia (28), and Atlantic and Prairie Provinces (33). The direct employment generated by the industry was similarly dispersed, with

Quebec, Ontario, British Colombia and the Atlantic and Prairie Provinces accounting for 38percent, 24percent, 23percent, and 18percent, respectively, of the pulp and paper industry employment.[9]

1.4.2 Industry Products and Revenue Shares

The Canadian pulp and paper industry produces a wide variety of products. Outputs from the Canadian pulp and paper industry can be categorized into four major groups: newsprint, paper other than newsprint, paperboards and building boards, and market[10] (or net output of) wood pulp. The "paper other than newsprint" category includes printing and writing papers, wrapping papers, sanitary and speciality papers, and building papers.

In the period from 1959 to 1994, the aggregate output of the industry[11] grew at an average rate of 2.95 percent per year. Aggregate output expansion was highest in the 1960's when output grew at an average rate of 5.20 percent per year. The average rates declined to 2.26 percent in the 1970s and then fell to only 1.43 percent during the 1980s, before rising again to a rate of 2.84 percent per year in the period from 1990 to 1994.

With an average growth rate of 5.35 percent per year over the period from 1959 to 1994, paper other than newsprint was the fastest growing product category of the Canadian pulp and paper industry. And within this category of outputs, writing and printing papers grew the fastest (at 7.31 percent). Other products that grew at rates faster than aggregate output were sanitary and specialty papers (4.34 percent), market wood pulp (4.17 percent) and paperboard (3.19 percent).

During the period from 1959 to 1994, the production of newsprint had increased to 1.61 times of what it was in 1959, production of paperboards and building boards increased to 3.44 times the 1959 level, pulp to 4.31 times, and paper other than newsprint output increased to 6.80 times. Within the last category, the output index for writing and printing paper was 12.90 times the 1959 level while sanitary and specialty papers production was 4.57 times of what it was in 1959. By 1994, the aggregate output of the industry had increased to 2.9 times the 1959 level.

Despite its relatively slow growth, newsprint has remained the most important source of revenue for the Canadian pulp and paper industry. The average contributions to industry revenue of newsprint, paper other than newsprint, paperboards and wood pulp were, respectively, 44.9 percent, 15.7 percent, 9.5 percent and 30 percent over the period of the study (i.e. from 1959 to 1994). The revenue share of newsprint declined from about 55 percent in the beginning of the period to less than 40 percent by the end of the period, while that of pulp rose from 22 percent to 31 percent by the end of the period. The fastest increase, however, occurred in the revenue share of paper other than newsprint, the contribution of which increased from only 12.3 percent in 1959 to 23.4 percent in 1994.[12] The revenue shares of paperboards and wrapping papers changed little.

1.4.2.1 Wood Pulp

Wood pulp is the major raw material in paper and paperboard making.[13] There are two principal categories of pulp: mechanical and chemical.[14] Canada is the second largest producer of wood pulp, accounting for 16.2 percent of world production, following the US which produces (and consumes) about 38 percent of total world pulp output. Canada's consumption of total world wood pulp output is only 9.7 percent. More than 35 percent of Canadian production of pulp is exported. This comprises more than 55 percent of Canadian production of chemical paper grade wood pulp and about 12 percent of the production of mechanical pulp. Canada is also the world's largest market pulp supplier, accounting for more than 25 percent of the world supply of market pulp.

Pulping is the process by which solid raw material (usually wood) is reduced to fibres. Wood contains four principal component groups.[15] Roughly 50 percent of wood is *cellulose* fibres[16], a versatile source of fibre for not only paper and paperboard making, but also a basic element in a variety of other products including rayon, explosives, photofilm, and other products requiring a cellulose base. The remaining 50 percent of wood consists of roughly equal amounts of *hemicellulose* and *lignin*. Hemicellulose serves as a binding agent between the cellulose and the lignin. Lignin is a complex substance that protects and binds the cellulose fibers together, giving rigidity and strength to wood. Wood also contains *extractives* (such as resins, oils, alcohols and fatty acids) which constitute 1.5 to 5 percent of wood.

Mechanical pulp is obtained through a mechanical separation of wood fibres from one another. This is most commonly done by forcing debarked logs against a huge revolving grindstone which shreds the fiber from the wood or simply by high speed refining of chips by subjecting the wood chips to millstone-like action of rotating discs. The first method is known as the s*tone groundwood* (SGW) method and was developed in the 1840s. The r*efiner mechanical pulp* (RMP) process was developed in the late 1950s.

Mechanical pulp is also known as "high yield pulp" because most of the components (85 to 95 percent) of the wood are retained in the final product. Their relatively lower cost and high opacity have made mechanical pulps a chief constituent for newsprint, directory and catalogue papers. However, paper made from mechanical pulp tends to be weaker because the fibres are damaged in the pulping process. Products made from mechanical pulps also suffer from some degree of discoloration or loss of brightness because the lignin has a tendency to yellow when exposed to heat or ultraviolet light (CPPA 1996c).

The most recent step in the evolution of mechanical pulps is the invention of *chemi-thermomechnical pulping* (CTMP).[17] In the CTMP process, wood chips are chemically treated prior to heating and mechanical defibration. Chemistry, temperature, and mechanical parameters can be varied to "custom tailor" the properties of the wood pulp output. The invention of the CTMP was preceded by another process, known as *thermomechanical pulp* (TMP) that reached commercial viability in the early 1970s. In the TMP process, mechanical separation of cellulose fibres is facilitated by softening wood chip inputs using steam. CTMP pulp has improved physical properties compared to TMP, SGW or RMP pulps.

Chemical pulping depends on chemical solvents that separate the cellulose fibres by dissolving lignin and wood extractives. For this process, the logs are first converted to chips and are "digested" or cooked for several hours under pressure in an alkaline or acidic chemical liquor at high temperatures. The cooking liquor is then remove by repeated washings to obtain only the pulp fibres and some occasional coarse particles which are separated by screening. Depending upon the species of wood and the pulping method, the fibres vary in colour from dark brown to a creamish white. A large portion are bleached, most often in chlorine, chlorine dioxide and calcium hypochlorite. The chemical pulping process results in a much lower yield than in mechanical pulping, 40 to 55 percent as opposed to 85 to 95 percent of the original wood. But chemical pulps are stronger, easier to bleach (whiten) and less likely to lose their brightness over time.

The two principal chemical pulping methods produce sulphate or kraft pulp and sulphite pulp. The methods are similar, but whereas sulphate cooking liquor is an alkali solution of sodium hydroxide (caustic soda) and sodium sulphide, sulphite liquor is an acid. In sulphate or kraft pulping, the chemicals are recovered and used again.

Sulphate or kraft pulp is known best for its strength and enjoys the most widespread use among pulps.[18] Unbleached kraft pulps are used chiefly in the manufacture of wrapping and bag papers and shipping sacks, as well as in paperboard for shipping containers. Bleached sulphate pulps are most important in the manufacture of a broad category of printing and writing papers.

Sulphite pulping, which was the dominant form of pulping until the 1930s, has been declining in relative importance for two reasons. First, although sulphite pulping produces a higher and brighter yield than that of the sulphate process, it is not as versatile with regard to the types of wood species it can handle. Second, the sulphite process does not allow the efficient recovery of chemicals used. As a result, currently the sulphite process accounts for less than 7 percent of the chemical pulps produced in Canada. Sulphite pulp is used in the manufacture of many book, bond, writing, sanitary and tissue papers. It is also used with mechanical pulp in newsprint manufacture.

In addition to sulphate and sulphite pulps, the Canadian pulp and paper industry produces several other types of chemical pulps. These include semichemical and dissolving and special alpha pulps. *Semichemical* pulp is manufactured by a process partly chemical and partly mechanical. The pulp usually is unbleached, and used mostly for the manufacture of corrugating medium, for use in corrugated board. *Dissolving and special alpha pulps* are exceptionally pure grades of bleached sulphite and bleached sulphate. Dissolving pulps are used in the manufacture of rayon, cellophane, explosives, and other products involving chemical conversion of the fibres. Because of their exceptional purity, high alpha pulps also have proven useful for certain specialty papers, among them filter, blue-print, and photographic-base papers.

1.4.2.2 Paper Making[19]

The basic process of paper making has not changed in almost 2000 years. It is based on the phenomenon that cellulose fibres in an aqueous solution will adhere to one another when the water is removed.[20] Hence, paper is made by first mixing the raw material with water to create a suspension of individual fibres, and then by forming felted sheets by evenly spreading this suspension on a porous surface or screen that permits much of the water to drain. Pressure and heat is used to remove the remaining water. The cellulose fibres bond, and we get a compact sheet.

This phenomenon was discovered in China in the year 105 AD, when the earliest known true paper still in existence was made from rags.[21] The art of paper making was confined to China for approximately 500 years before it reached Japan in 610. The secret of paper manufacture reached the western world by way of Arab caravan, which had taken Chinese prisoners in battle, and tortured them to reveal the techniques of their craft (CPPA 1974).[22] The first European paper mill was built in Moorish Spain in 1150 (Murray 1992). From 1150 to the discovery of the groundwood pulping technology in the middle of the 19th century, the feedstock of paper making remained recycled cellulosic materials such as rags, rope, fish nets, and burlap.

Paper was made entirely by hand, sheet by sheet, until the first practical paper machine was developed in France in about 1799. The first Canadian paper mill was built at St. Andrews, Argenteuil County, Quebec in 1803-5. The mill manufactured writing, printing and wrapping papers. In the period from 1817-23,many more paper mills were built in Portneuf County, Quebec. The first paper mill in the Maritimes was built near Halifax in 1819, while the first paper mills in Ontario started up in 1827. Currently, the Canadian pulp and paper industry consists of 162 pulp and paper mills each employing on average 416 people.

Most paper today is formed on a *Fourdrinier machine*.[23] The central feature of this machine is a continuous belt of wire mesh or screen (known as the *former*) that moves horizontally and is kept level by means of tension and the support of rollers. Watery pulp is spread on the screen. Much of the water is drained off during the brief movement of mixture on the screen, leaving behind a continuous sheet of wet pulp. This stock of bonded fibres is then pressed between rotating rolls to force more water out. A fully formed paper is then obtained. The drying process is completed by passing the paper through a series of steam-heated rolls. The paper is then given a machine finish through *calendering*, pressing between smooth solid steel cylinders. On a fast machine, it is only a few seconds from the time the stock moves onto the screen until it emerges as a ribbon of paper one hundred yards away.

Modern alternatives to the Fourdrinier paper machine are a class of paper machines known as *twin-wire machines*. In theses machines, fibres are formed into a sheet between two conveyor belts, enabling the removal of water from both sides of the sheet simultaneously. The advantages of this method is that it results in sheets with more uniform surfaces and higher production speeds. For more details on paper making machines, see CPPA (1974) or McCubbin, Bonsor and Owen (1990), for example.

Paper products with different properties can be obtained by modifying the sheet of cellulose fibres in innumerable ways. *Dye* may be added to the pulp solution to colour the paper. A *filler* (such as china clay) may be added to improve the printability, opacity, and appearance. Or the resistance to penetration by liquids may be improved by using a *size*, such as rosin or wax. *Coating materials* (such as mineral matter, adhesive, waxes, or water proofing agents) may be added before or after the paper is made to improve the surface of some high-grade papers and paperboards (CPPA 1974,1996c).

1.4.2.2.1 Newsprint

Canada enjoys a long standing tradition as the world's largest producer and exporter of newsprint.[24] More than 25 percent of the world's newspapers are printed on Canadian paper. In 1995, Canada produced 9.25 million tonnes of newsprint, contributing 26.7 percent of the total world newsprint production. Canada was followed by the US (18.4 percent), Western Europe (14.5 percent), Nordic Countries (12.8 percent) and Japan (8.9 percent). On the other hand, Canada's newsprint consumption constituted only 3.5 percent of world demand for newsprint. Close to 90 percent of newsprint production is exported, making Canada the world's largest exporter of newsprint – with 50.57 percent of the export market. The US is by far the largest buyer of Canadian newsprint exports, accounting for 72 percent of the newsprint export demand. The other major markets for Canadian newsprint exports are Latin America (8.6 percent), Asia (7.75 percent), Western Europe (7.3 percent) and Japan (3.2 percent).

Newsprint is made from about four-fifths mechanical and one-fifth sulphite or sulphate pulp. Recently the trend has been towards a partial substitution of the chemical pulp content by recyclable paper, which accounts for 9.4 percent of the newsprint fibre source according to statistics for 1992 (CPPA 1996a).

1.4.2.2.2 Other Papers

The industry produces a wide variety of other papers besides newsprint. These include printing and writing papers, kraft or wrapping papers, and sanitary and specialty papers. *Printing and writing papers* is a broad category that includes hundreds of paper grades. The fine paper grades are formed from carefully bleached chemical wood pulps. (Rag pulp is still used for many of the finest printing and writing papers.) Because of advances in mechanical pulp such as CTMP, an increasing proportion (currently 55 percent) of printing and writing papers is now made from mechanical pulp.

Kraft paper is a strong and versatile class of papers used as paper bags, wrapping papers and for forming sacks that carry a wide variety of products. Kraft paper is mainly made from unbleached kraft pulp. Although its growth is less dramatic than in the case of printing and writing papers, the industry's output of *tissue and specialty papers* has been steadily increasing to include products for use in the electrical field and in the manufacture of paper containers, paper cups, napkins, towels, handkerchiefs, diapers, and grease-proof and water-proof papers for wrapping foods. The industry also produces numerous specialty products including asphalt paper, wall paper, slip cover fabrics, and carpet yarns and fabrics (CPPA 1974). An increasing proportion of the fibre source for sanitary papers is also coming from recyclable papers which have been replacing mechanical and chemical wood pulps as inputs. For example, in 1992, 59.1 percent of the fibre furnish for sanitary papers came from recyclable papers (CPPA 1996a). Chemical wood pulp accounted for most of the remaining. This is a dramatic increase in recyclable paper content compared to 1982, when only 23.4 percent of the fibre furnish came from recyclable paper.

In 1995, the Canadian pulp and paper industry produced 4.8 million tonnes of different printing and writing grade papers, 544 thousand tonnes of wrapping papers, and 617 thousand tonnes of sanitary and specialty papers. About 76 percent of printing and writing papers and 72 percent of wrapping papers produced in Canada were exported. Most sanitary and specialty papers were, however, consumed in the domestic market, only 17 percent finding their way into the international market. The US was by far the largest buyer (89.7 percent) of Canadian exports of papers other than newsprint, with Western Europe (2.4 percent) and Latin America (2.6 percent) following far behind.

1.4.2.2.3 Paperboard

Paperboards include a wide variety of products, ranging from light paper products that enclose compact discs to heavy cases that carry refrigerators. There are two major categories of paperboards: *Boxboards* and *Container Boards*. *Container boards* include liners, corrugating medium, and container chipboards. The industry also produces building boards of many types, including acoustic board, shoe board, ceiling tiles, and decorative board. Current Canadian output of paperboards totals 3.4 million tonnes, about 70 percent of which is container board. Only about 40 percent of paperboard production is exported. The US is by far the largest buyer of Canadian exports of paperboard, accounting for 64 percent of Canadian exports, followed by Asia (excluding Japan) 17 percent and Western Europe (11.2 percent).

1.4.3 Input Use and Cost Shares

Seven input categories were identified in this study. These include energy, wood residue, pulpwood, non-wood materials, production labour input, administration workers, and capital. The non-wood materials category includes: 1) industrial chemicals 2) containers and packaging materials and supplies, 3) all other operating, maintenance and repair supplies, 4) amount paid to others for work done on materials and supplies owned by the establishment, 5) textile and rags, and 6) recycled and waste paper and paperboards.

Aggregate input grew at an average rate of 2.54 percent per year from 1959 to 1994. Wood residue (8.6 percent), non-wood materials (4.47 percent) and capital (3.79 percent) grew at a higher rate than aggregate input. But the use of pulpwood increased at the lower rate of 0.21 percent, bringing down the average rate of virgin fibre input growth rate to 2.65 percent per year and that of total material inputs to 3.51 percent. The average annual growth rate for energy was 2.04 percent, mainly because of energy input increases in the period from 1959 to 1974.

The input of production labour declined in the 1980s and the 1990s and had the lowest average growth rate of all inputs in this study, at 0.12 percent per year, for the period from 1959 to 1994. The number of administration workers also showed a negative trend in the 1980s and 1970s, attaining an average rate of growth of 0.87 percent for the period from 1959 to 1994. Aggregate labour input declined in the 1980s and early 1990s after increasing at the rate of 2.54 percent in the 1960s and 0.51 percent on average in the 1970s. The average rate of growth of aggregate labour input was 0.30 percent for the period from 1959 to 1994.

Wood residue input had increased by twenty fold over the period from 1959 to 1994, while the inputs of pulpwood and production labour were only 8 percent and 4 percent higher in 1994 than in 1959, respectively. Energy consumption had doubled between 1959 and 1974 and changed little since then. The industry was employing 1.36 times more workers, 3.8 times more capital and 4.8 times more non-wood materials in 1994 compared to what it utlized in 1959.

Material inputs accounted for the highest average cost share (52 percent) for the period from 1959 to 1994, followed by labour (25.8 percent), energy (11.3 percent) and capital (10.8 percent). For specific materials, the average share of fibre was 28.1 percent in total input costs while that of non-wood materials was 24.1 percent. While the cost share of wood residue increased substantially (from 2.2 percent in 1959 to 14.6 percent in 1994), the cost share of virgin fibre in total declined from 32 percent in 1959 to 22.7 percent by 1994 because of the decline from 29.8 percent to 8 percent of the share of pulpwood in total cost.

The cost share of non-wood materials increased from 17.2 percent to 28.9 percent over the study period. The cost share of labour decreased from about 28 percent to about 21 percent over the period, mainly due to the decrease in the cost share of production labour (from 21 percent to 15 percent). The share of administration labour changed very little (from 6.6 percent in 1959 to 5.7 percent in 1994).[25] Energy's cost share increased from 9.3 percent in 1959 to 12.9 percent in 1994. By the end of the period, however, energy had a lower cost share compared to production labour, wood residue, non-wood materials or capital, but a cost share higher than that of administration workers or pulpwood.

1.4.4 Environmental Effects and Regulation

Although the Canadian pulp and paper industry is a major contributor to the national economy in terms of national income, employment and foreign exchange earnings, it has also been the focus of considerable attention from the public and provincial and federal governments because of its environmental effects. The industry consumes vast amounts of forest resources every year for its production of pulp and paper. The industry is also a significant source of water and, to a lesser extent, air and land pollution.

Major air pollutant emissions from the pulp and paper industry include particulate matter, sulphur dioxide, total reduced sulphur (TRS) and volatile organic compounds (VOC). The term TRS refers to a group of compounds that include hydrogen sulphide, methyl mercaptan, dimethyl sulphide, and dimethyl disulphide. The TRS are the compounds that cause the characteristic foul odour associated with pulp mills; they have very low odour threshold and can be discerned by smell at concentrations that are seldom hazardous to human health (Murray

1992, p.8). Other air pollutants generated by the pulp and paper industry include carbon monoxide, chlorine, chlorine dioxide and nitrogen oxides.

The industry is not a significant contributor to global air pollution problems related to acid rain and global warming. It is a source of localized and nuisance odorous air pollutants (Gaston 1993, p.19). It is estimated that the industry contributes about 5.6 percent of common air contaminants from known industrial sources (Sinclair 1990, p. 34). Recent estimates indicate that the pulp and paper industry's contribution to national air emissions range from lows of 0.84 percent for CO and 1.9 percent for VOC to a high of 7.7 percent for PM, with NO_x and SO_2 in between at 2.5 percent and 3.8 percent of the total man made sources (Environment Canada 1995).

However, the Canadian pulp and paper industry is estimated to be the source of 50 percent of all the waste dumped into the nation's waters (Sinclair 1990). Thus, most of the attention on the Canadian pulp and paper industry has focused on its water pollution output. The pulping, bleaching and paper making processes generate a large volume of water effluents containing pollutants, mainly wood particles, organic material and waste chemicals from the pulping and bleaching process.[26] The wood particles are measured as *total suspended solids* (TSS)[27] and are expressed in kilograms.[28] Suspended solids increase turbidity, upset aquatic habitat and ruin fish spawning beds. Organic matter contained in mill effluents stimulates algal growth and consumes dissolved oxygen, thereby reducing the ability of the water to support aquatic life. This oxygen consumption potential of dissolved organic material is generally measured as ***biological oxygen demand*** (BOD) expressed in kilograms per tonne of product.[29]

Mill effluents also carry toxic substances such as resins and fatty acids. In addition, in the case of mills that use elemental chlorine for bleaching, a very large number of organochlorine compounds are generated and discharged into the environment (Murray 1992, Gaston 1993). Some of these compounds are known mutagenic and carcinogenic agents (Murray

1992). Dioxins and furans have also been identified in emissions from chlorine bleaching and from burning of black liquor during the recovery of chemicals used in the sulphate pulping process. Dioxins and furans are considered to be highly toxic by Environment Canada (Gaston 1993).

Recently, the pulp and paper industry faced new constraints regulating the release of various pollutants. Total suspended solids, biological oxygen demand and, more recently, dioxins and furans are among the indicators selected by regulatory authorities in Canada for the purpose of monitoring pulp and paper industry pollution. In the period from 1971, when regulations on the pulp and paper industry were first introduced, to 1991, only new mills and mills that underwent significant expansion were subject to restrictions under the Fisheries Act. In 1992, the federal government introduced new regulations that apply to all mills. The 1992 regulations, under the Fisheries Act, apply to discharges of BOD, TSS, and effluents acutely lethal to fish.[30] The new regulations passed under the authority of the Canadian Environmental Protection Act (CEPA) require the elimination of any measurable levels of dioxins and furans from mill effluents (Environment Canada 1992a).[31] Some provinces have also passed regulations using the more stringent generic classification of Adsorbable Organic Halogen (AOX).[32]

1.4.5 Pollution Abatement

The pulp and paper industry has spent large sums of money to reduce or eliminate discharge of dioxins and furans in response to publicity and public fear of dioxins which peaked with the discovery of dioxins in milk cartons (Murray 1992). Between 1988 and 1993, discharge of dioxins and furans fell by 98 percent (OECD 1995).

Pollution abatement in the industry has followed two general approaches. The first approach involves new trends toward in-plant process changes, including improved delignification (e.g. oxygen delignification) and partial or complete replacement of chlorine for bleaching with such chemicals as chlorine dioxide, hydrogen peroxide (Murray 1992). The second approach involves the use of end-of-the-pipe primary and secondary effluent treatment facilities (see, for example, McCubbin, Bonsor and Owen 1990; McCubbin Folke1993). This second approach has been used to reduce the discharge of traditional pollutants such as TSS and BOD.

The purpose of the primary treatment is the removal of suspended solids from the effluent. This usually involves the use of gravity clarifiers or settling basins and removes from 80 to 90 percent of the settleable portion of the suspended solids, and also 10 percent of the total BOD (Gaston 1993; McCubbin, Bonsor and Owen 1990). The objective of the secondary treatment is to reduce, using biological processes, BOD by from 70 to 95 percent and to render the effluent non-lethal to fish (Gaston 1993; McCubbin, Bonsor and Owen 1990).

In Canada, secondary treatment almost universally involves the use of aerated lagoons that utilize naturally occurring micro-organisms (bacteria, algae, fungi, protozoa and other forms of life) to convert much of the organic material in mill effluent into water, carbon dioxide or organic solids. Secondary treatment, however, is not effective in eliminating dioxins and furans (Gaston 1993). Moreover, the aerobic secondary treatment facilities in use are more efficient in treating low molecular weight pollutants, such as methanol, than in treating the high molecular weight materials, such as chlorinated lignins (McCubbin, Bonsor and Owen 1990). Recent experiments aimed at improving the effectiveness of secondary treatment in reducing resin acids and organochlorines include three stage aerobic-anaerobic-aerobic treatments (Murray 1992). The technology for effluent treatment continues to change.

1.5 Sources and Construction of Data Used in the Study

Time series output and input quantity and price data were collected for the national pulp and paper industry of Canada for the period from 1959 to 1994. Output data were collected mainly from Canadian Pulp and Paper Association's (CPPA) *Reference Tables*[33] (1965 to 1996). Average export product values were used for output prices. More than 85 percent of newsprint, and most of the market wood pulp, printing and writing papers and wrapping papers produced in Canada are exported.[34]

Input use quantities and prices were collected from different Statistics Canada catalogues and/or obtained by special request from Statistics Canada. Most of the published Statistics Canada data for the pulp and paper industry group (SIC 271) is obtained from *Pulp and Paper Mills* (Catalogue No. 36-204, 1959-1984) and *Paper and Allied Products Industries* (36-250, 1985-1994). The publication *Canadian Forestry Statistics* (Catalogue No. 25-202, 1962-1993) contains additional information on the industry. Owing to the partial suspension of the Census of Manufactures in 1987 and 1991, some figures for these years had to be imputed from price indices, trends in the variables themselves, shares, and average input-output coefficients.

Additional data (known as "Principal statistics") for the period from 1961 to 1994 were obtained from Statistics Canada by special request. For 1959 and 1961 the data were collected from the 1960 publication of Statistics Canada Catalogue No.36-204. The Statistics Canada "principal statistics" include the following: production workers, production hours paid and production wages, number of administration workers and salary paid, cost of fuel and electricity data, manufacturing and total materials use, shipments and value added data.

Energy data for the period from 1959 to 1974 were collected from Statistics Canada Catalogue No.36-204. Additional data for the years 1975-1986 and 1990-1994 were obtained by special request from Statistics Canada. Energy consumption was converted into gigajoules using the following conversion factors: 26 million British Thermal Units (BTU) per metric ton of coal and coke; 0.1492 million BTU per gallon of gasoline; 0.1796 million BTU per gallon of (heavy) fuel oil; 22.25 million BTU per cord of wood; 1 Million BTU per thousand cubic feet (M.Cu.ft) of natural gas; 0.117 million BTU per gallon of liquefied petroleum; 3.412 million BTU per thousand kWh of electricity; and 1,054.615 joules per BTU. These conversion factors were obtained from Statistics Canada (1969) Catalogue No.57-505, entitled *Detailed Energy Supply and Demand in Canada*.

To fill in missing energy data for 1987, 1988 and 1989, we constructed implicit energy quantity data as follows. First, energy price indexes for these years were used to calculate per gigajoule energy costs. Implicit energy data were then calculated by dividing these energy prices into cost of fuel and electricity data. The energy price indexes used in these calculations were derived from price indexes for fuel oil, natural gas and electricity by averaging these indexes using the energy cost shares scaled to add up to one. These three sources account for 90 percent of the cost of energy.

Materials consumption data were collected from Statistics Canada Catalogue No.36-204 and from Catalogue No.25-202. The CPPA's (1989, 1993) *Role of Canadian Wood Pulp in World Markets* was the source of some own wood pulp consumption data for Canada for 1983, 1984, 1987 and 1991.

Inputs of materials other than wood were calculated as follows. The money value of expenditures on materials other than fiber was calculated by subtracting the values of virgin fiber (pulpwood and wood residue), and purchased wood pulp from the value of total materials for this industry. This estimated value of non-wood materials was then divided by a price index for non-wood materials estimated as a share-weighted average of the price indexes of the Industrial Inorganic Chemicals Industry Selling Price Index (CANSIM[35] data series D694146) and the GDP implicit deflator. The GDP implicit deflator was used as a price index for a variety of inputs. These include: 1) containers and packaging materials, 2) operating, maintenance and repair supplies purchased and used (excluding fuel and electricity), and 3) amount paid to other establishments for work done on materials owned by the establishments classified to the pulp and paper industry. The non-wood materials figures thus calculated were used as implicit quantity indexes.

Shipment quantity and value data for the period from 1959 to 1984 were collected from Statistics Canada Catalogue No.36-204 (1959 to 1984 publications). For the period from 1985 to 1994, the shipments data were collected from Statistics Canada Catalogue No.36-250 and from the 1995 and 1996 *Selected Forestry Statistics Canada* publications of the Canadian Forestry Service. Average shipment prices were calculated from the shipment quantities and values data. Whenever this procedure for the calculation of average prices was not possible because of missing data points in the period after 1983, appropriate product price indices from CANSIM were used to calculate average shipment price estimates.

Export quantity and value data for the period from 1959 to 1994 were collected from Statistics Canada Catalogue No.25-202 (1962 to 1993). Average export prices were calculated by dividing export values data by export quantities.

Recently revised capital stock data for the pulp and paper industry were obtained by special request from the Investment and Capital Stock Division of Statistics Canada. These estimates are obtained from annual capital expenditures using the perpetual inventory method (PIM). See Hulten 1990, for example, for a description of the PIM. The capital stock data were constructed by Statistics Canada using the following procedures. Discards are calculated using a truncated normal distribution for service lives. This discard function has an advantage over the simultaneous exit method used previously. The bell-shaped function reduces the so-called "echo effect" by allowing for variation in the age at which identical assets are removed from the stock. A normal distribution with a standard deviation equal to one quarter of the mean is used. The truncation is made at twice the standard deviation and then the total area under the curve is adjusted by vertically raising the curve. Recently revised service lives estimates were used in the calculation of stock estimates.

The discard function is used to weight the individual depreciation rates for different subcohorts of a given vintage of capital. Geometric form was assumed for depreciation. There is empirical evidence that the pattern of depreciation for Canada follows a geometric form . (See the 1994 *Fixed Capital Flows and Stocks* publication of Statistics Canada).

The capital consumption allowance charged in year *i* against an asset of age *x* ($CCA_{i,x}$) is given by:

$$CCA_{y,a} = GI_{(y-a+1)}.DR_{y,a}$$

here $GI_{(y-a+1)}$ is capital expenditure in year (y-a+1) and $DR_{y,a}$ is the depreciation rate in year *y*

$$DR_{y,a} = F(a,L).W(L)_{a,y}$$

for assets of age *a*. The latter is a weighted average calculated as follows:

in which $F(a,L)= (2/L).\ (1-2/L)^{(a-1)}$ is the geometric depreciation rate for assets of age *a* with a service life of L and $W(L)_{a,y}$ stands for the portion of assets of age *a* with service life L in year *y*.

We used the following formula due to Boadway (1985) to calculate the service price of capital to be used with the capital stock data obtained from Statistics Canada:

$$r_k = q.\left(\frac{i+\delta+r_q-\pi}{1-\tau}\right).(1-\phi)\left(1-\frac{\tau\alpha}{i+\alpha}\right)$$

where *i* is the opportunity cost of capital, δ is the capital depreciation rate, r_q is the rate of growth in the acquisition price of capital *q*, π is the rate of inflation in the economy, τ is the corporate income tax rate, ϕ is the investment tax credit, and α is the percentage capital consumption allowance.[36]

The above capital user cost formula is appropriate for the Canadian tax system (Boadway 1985). Because of a difference in the treatment of investment tax credit in the calculation of the depreciation base for tax purposes, the appropriate capital user cost formulas for the US and Canada should be different. In Canada, this depreciation base is smaller than actual investment by a proportion equal to the investment tax credit. In the US this proportion is equal only to one half of the investment tax credit; i.e. the US tax system is more generous in this respect.

For the calculation of the geometric depreciation rate (δ), we used the following sample mean service lives: 28 years for building and engineering construction, 18 years for machinery and equipment, and 20 years for all components of (total) capital. The annual geometric depreciation rate was calculated as 2 divided by the average service life. The inflation rate (π) was calculated from the implicit GDP deflator. Bank of Canada's Scotia-McLeod industrial bond yield average on long term investment (CANSIM data series B14016 and B14019) was used as an opportunity cost of capital, i. The taxation data needed for the calculation of the service price of capital were collected from publications of the Tax Foundation of Canada and the Canadian Institute of Chartered Accountants. The corporate income tax and investment tax credit rates vary from province to province. The overall corporate income tax rates and investment tax credit rates for Canada were estimated as value-added share weighted averages of the corresponding provincial rates.

NOTES

[1] These average growth figures are taken from Prichett (1988).
[2] The figures quoted here were calculated from a table of figures in Fischer (1988).
[3] This could be associated with demographic shifts from baby boomers and women's increased participation in the labour market.

[4] See also Lipsey (1996), Fischer (1988), Jorgenson (1988), Griliches (1988) and Repetto *et al* (1996). Based on empirical analysis using data for the United States, Zvi Griliches also suggests that a slowdown in the rate of creation of knowledge might have contributed to the retardation in productivity. For an opposite view point on this particular possibility, see Richard Lipsey's historical analysis of technological progress.

[5] These authors also undertake a similar study of oil refinery and steel mills. They find that the productivity loss equivalent associated with a $1 expenditure is $1.35 for oil refineries and that a loss of $3.28 applies for steel mills.

[6] According to Porter and van der Linde, the "product offsets" occur because the environmental regulation creates better, safer or more easily disposable products or lower costs of production due to input substitution or reduced packaging. The "process offsets" occur because of such factors as higher process yields, less downtime, materials savings, lower energy consumption, utilization of by-products and conversion of waste into valuable forms.

[7] BOD and TSS stand for biological oxygen demand and total suspended solids, respectively. These two water pollutants are described in more detail later in this chapter.

[8] The total merchandise trade balance was $71.1 billion for 1990-95.

[9] These figure are from "Principal Statistics" data obtained from Statistics Canada by special request.

[10] The net wood pulp output referred to here was obtained by subtracting wood pulp consumption by the industry from total wood pulp production. These figures are not necessarily the same as market pulp figures reported in publications by the Canadian Pulp and Paper Association (CPPA). Market pulp, as defined by CPPA, excludes wood pulp shipped to subsidiary or affiliate mills in Canada or the US. The term "market pulp" is used synonymously with net wood pulp output in this section for ease of reference only.

[11] We used the Tornqvist index formula for all the input and outputs aggregations referred to here and elsewhere in this paper.

[12] Within this output category, the share of writing and printing papers in industry revenue had increased from less than 6 percent of total industry revenue in the beginning of the period to about 16 percent by 1994. The share of sanitary and speciality papers had increased from less than 2.5 percent to about 6 percent.

[13] Before a process for manufacturing groundwood or mechanical pulp was invented in Germany in 1843, paper making was largely based on linen and cotton rags. The chemical process for manufacturing pulp by cooking wood chips in chemicals was invented in England in 1851.

[14] The following discussion of the two different types of pulp is based on CPPA (1974, 1996c).

[15] See, for example, Kringstad and Lindstrom (1984), CPPA (1974, 1996c) or Murray (1992).

[16] The fibres are hollow, tubular cells. Cellulose is the major component of the cell walls of wood fibres.

[17] The first mill using the CTMP process commenced operation in 1978 (CPPA 1996c).

[18] "Kraft" is a German word for strong.

[19] The description of the paper making process is mainly based on CPPA (1974).

[20] This happens through the hydrogen bonding of the cellulose molecules.

[21] Paper is predated by Egyptian papyrus and Chinese silk cloth which had served as writing materials. Egyptian papyrus is not considered a form of paper because it is made up of layers rather than a bonding of discrete fibres.

[22] The art reached Central Asia in about 750, and Egypt in about 800 but paper was not manufactured there until 900.

[23] This Froudrinier machine for making "endless paper" was patented in England in 1807. The first machine of this type in Canada was installed at Portneuf, Quebec, in 1843.

[24] Canada has been the most important exporter of the pulp and paper since 1918, i.e. shortly after the lowering in 1909 and then the removal in 1913 of US import tariffs on newsprint (CPPA 1974). See also Uhler, Tonwsend and Constantino (1987) for a discussion of the historical forces that shaped the output mix and trade pattern of the Canadian pulp and paper industry.

[25] Although production labour input had increased little (from 107.1 million hours in 1959 to 111.6 million hours in 1994), the production workers' wage rate increased from its 1959 level of $2.29 per hour, to $3.80 in 1970, $10.79 in 1980, $20.02 in 1990 and $22.90 in 1994. The average annual earnings of an administration worker also showed a similar increase, from $6,619 per worker in 1959 to $10,342 in 1970, to $27,356 in 1980, to $52,552 in 1990 and to $60,644 in 1994. The number of administration workers in the industry had risen from 11708 workers in 1959 to 20712 in 1981 but declined afterwards and was only 15,889 by 1994. The industry had 51,607 production workers in 1994.

[26] Mills producing only paper, referred to as non-integrated paper mills, also discharge water contaminated with fine fibres in the stock preparation and paper making processes. Coating materials used in the paper mills (e.g. starch, latex and other coating materials) can also cause significant biological oxygen demand. Otherwise, the BOD discharge from non-integrated paper mills is considered to be small or negligible (McCubbin *et al* 1990).

[27] The alternative name total suspended matter (TSM) is also used instead of TSS. The latter term is used here.

[28] Suspended solids are measured as the dry weight of the solids retained on standard filter paper (McCubbin 1993).

[29] BOD is determined by measuring the quantity of oxygen used in biochemical oxidation of compounds containing carbon and nitrogen in a specified time, at a specified temperature and under specified conditions. The standard measurement in North America is made for five days at 20^0 C and neutral pH (McCubbin 1993).

[30] These regulations can simplistically be summarised as maximum monthly average rates on BOD and TSS of 7.5 and 11.3 kg per tonne of product, respectively. The maximum daily regulations on these two pollutants are, respectively, 12.5 and 18.8 kg per tonne of product. See Department of Fisheries and Oceans (1992).

[31] Additional new regulations under CEPA limit the use of defoamers and wood chips treated insecticides (Environment Canada 199b).

[32] AOX includes all halogen compounds, not just organochlorines. In Ontario, British Colombia and Quebec the regulations limit AOX discharges to only 1.5 kg per tonne effective by 1993 (Murray 1992).

[33] The newsprint production quantity data from CPPA are exactly the same as those from Statistics Canada; the production data from the two sources are also very similar for paperboards and building boards, for wood pulp and for paper other than newsprint.

[34] The average export price figures were almost exactly equal to average prices calculated from shipment data for wood pulp; the two series were very close for paperboard for all periods, and for newsprint, especially before 1980. For paper other than newsprint, shipment prices are consistently higher than average export prices, but both price series have similar trends.

[35] CANSIM stands for Statistics Canada's Canadian Socio-Economic Information Management System, a database containing more than 650,000 items.

[36] The value $q.(1-\phi-\frac{\tau\alpha(1-\phi)}{i+\alpha} = q.(1-\phi)\left(1-\frac{\tau\alpha}{i+\alpha}\right)$ measures the effective price of capital, i.e. the acquisition price of capital q net of the investment tax credit ϕ and the present value of tax depreciation on a declining balance basis or $\frac{\tau\alpha.(1-\phi)}{i+\alpha}$. The present value of tax depreciation is the sum of yearly write-offs $\tau\alpha.(1-\phi)(1-\alpha)^t$ discounted by the opportunity cost of capital $(1+i)^{-t}$. The user cost for capital is derived by equating the marginal net of tax return on investment (i.e. $(1-\tau)$ times marginal return on investment) to the cost of holding capital, which is the sum of annual cost of depreciation and financing $(i+\delta-r_q-\pi)$ multiplied by the effective purchase price of capital. See Mintz (1996).

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CHAPTER 2 Index Number and Distance Function Analysis of Productivity and Efficiency

2.1 Introduction

Several attempts have been reported in the literature to measure productivity growth in the Canadian pulp and paper industry. Among the studies conducted in the last fifteen years, Sherif (1983) and Martinello (1985) use cost function approaches to analyze data for the periods from 1957 to 1977 and 1963 to 1982, respectively. Frank *et al* (1990) use data for the period from 1963 to 1984 to analyze productivity trends using index number and cost function techniques. More recently, Hsue and Buongiorno (1994) compared the productivity performance of the pulp and paper industries in the US and Canada during the 1961 to 1984 period using index number and nonparametric techniques.

This study attempts to analyze technical efficiency and productivity trends in the Canadian pulp and paper industry. It contributes to the literature in the following ways. First, the analyses in this study are based on data covering a longer period (1959 to 1994), extending the period covered in empirical studies of the industry beyond 1984. Most studies to date have covered the period only up to the early 1980s. Second, recently revised capital stock estimates from Statistics Canada (1994,1996) are used in this study. Third, two alternative approaches – input distance functions and index numbers – are used. Input-based Malmquist productivity growth estimates are derived from Tornqvist productivity indexes and the results are compared with similar estimates calculated from the estimated input distance function. Finally, the study deals with productivity growth and efficiency in an integrated way; most previous productivity studies ignored changes in the degree of productive efficiency.

This chapter is organized as follows. In the next section, general productivity concepts and sources of productivity change are discussed. The section also discusses approaches to productivity measurement that have been followed in the empirical literature. The study results reported in this chapter are based on analyses conducted using input distance function and Malmquist productivity indexes. The definition and properties of input distance functions in general as well as the functional form and the estimation procedures used in this study are discussed in the third section of the chapter. The fourth section presents Malmquist productivity concepts. The relationship of these indexes to the most commonly used index number formula, the Tornqvist index, are also discussed in that section. The results from index number and from input distance function analyses are presented and compared to results from other studies on the industry in the fifth section. The last section summarizes and concludes the presentation in this chapter.

2.2 Productivity Measurement

At the elementary level, productivity is simply defined as the rate of output per unit of input utilized. For a production technology involving one homogeneous output and one homogeneous input, this simple definition serves well. In fact, most of the alternative definitions of productivity growth that have been suggested in the literature in one way or another turn out to be equivalent in the case of one output, one input production processes. In particular, the following definitions of productivity are equivalent: ratio of output quantity index to input quantity index; ratio of technical coefficients (or average products) relating output to input; deflated revenue divided by deflated cost; output quantity index divided by deflated cost; and deflated revenue divided by input quantity index. A definition suggested by Jorgenson and Griliches (1967) in which productivity is measured as the ratio of input price index to output price index also is equivalent to the above five alternative definitions if costs equal revenue in each of the periods. See Diewert (1989, pp. 3-11) for these results.

The definition and measurement of productivity for technologies involving multiple outputs and/or multiple inputs is less straightforward. Recent advances in productivity measurement have focused on total productivity measures (TFP). Total factor productivity is based on the comparison of aggregates of outputs to aggregates of inputs. A central problem in the measurement of total factor productivity relates to the choice of aggregation methods. First, the generalizations to multiple output and input production processes of alternative productivity definitions do not lead to results that are equivalent (Diewert 1989). Second, there is no agreement on how the different measures ought to be generalized. That is, the choice of aggregation methods is enormous and choosing from the alternative conceptual measures of productivity change is not an easy task (Diewert 1989).

2.2.1 Sources of Productivity Change

Regardless of the multiplicity of inputs or outputs, observed productivity gains or losses, as measured by aggregate measures of output to aggregate measures of input, generally occur due to at least three important factors: changes in the degree of efficiency with which resource inputs are utilized; production scale effects; and changes in the state of the technology (Nishimuzi and Page, 1982; Perelman 1995). These can most easily be illustrated using a neoclassical production function, as in Figure 2.1, that relates the level of input (X) to the maximum output level of output (Q) that can be produced. $F^1(X)$ and $F^2(X)$ represent the production technologies in periods 1 and 2, respectively.[1]

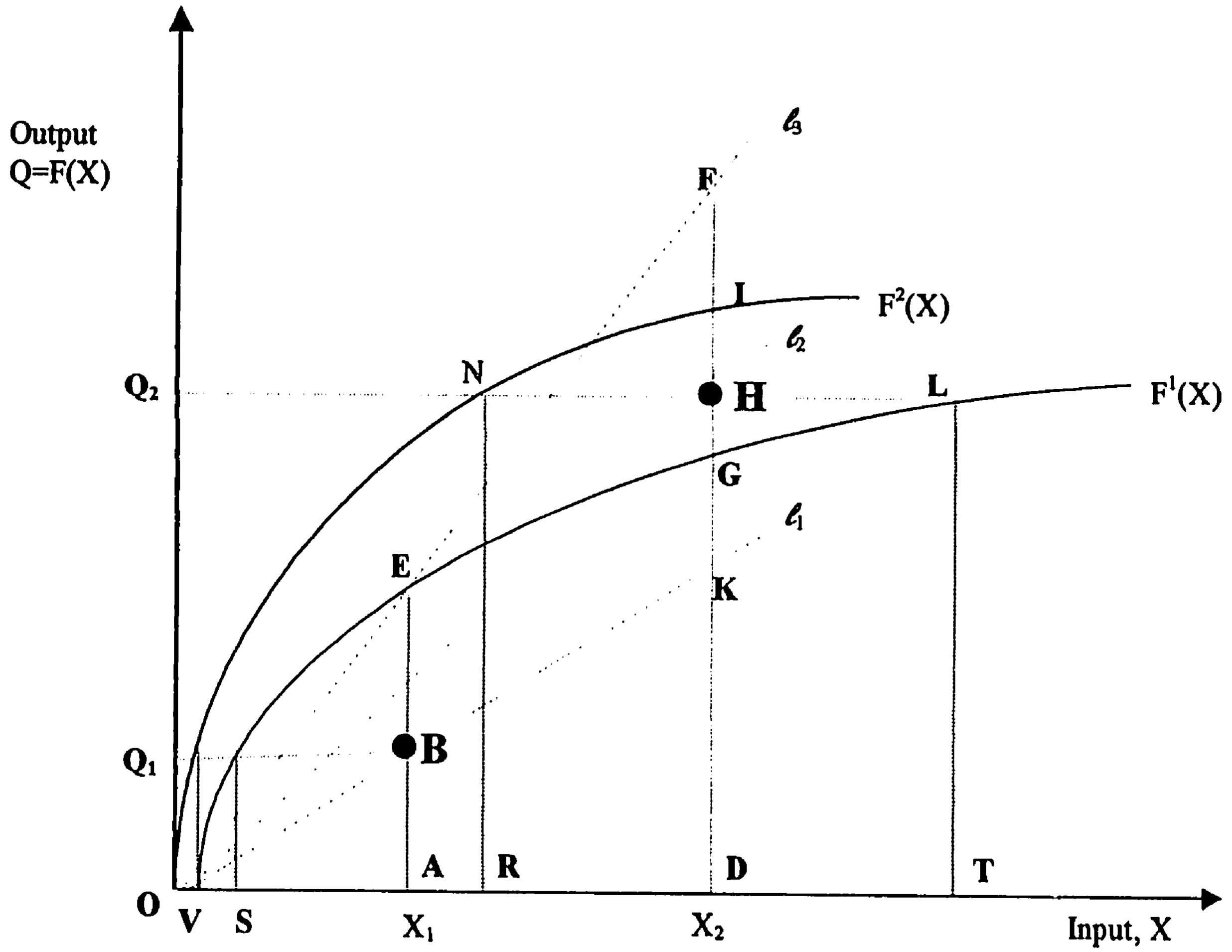


Figure 2.1 Decomposition of Total Factor Productivity

In period 1, the producer is operating at point B, using OA or X_1 units of the input to produce AB or Q_1 (rather than AE) units of output. In the second period, the producer is operating at point H, producing DH or Q_2 units of output using OD or X_2. Production in both periods is characterized by technical inefficiency. Using an *output-oriented*[2] Farrell-type (1957) measure, we can determine the level of technical efficiency (TE) in a given period by the ratio of actual output to the maximum output that can be produced using the same quantity of inputs, given the prevailing technology. This gives us technical efficiency levels of AB/AE and DH/DI for periods 1 and 2, respectively.

The level of productivity has changed from period 1 to period 2; points H and B lie on different rays through the origin. The three components of the total productivity change accompanying the move from point B to point H can be identified as follows. First we have productivity changes due to the change in the efficiency with which the input was used in period 2 compared to period 1. This is given by the index of technical efficiency change (ITEC), which is greater (less) than unity if there has been an increase (decrease) in TE.

$$ITEC = \frac{TE \ \ in \ \ period \ \ 2}{TE \ \ in \ \ period \ \ 1} = \left(\frac{DH}{DI}\right) \Big/ \left(\frac{AB}{AE}\right)$$

The scale at which productive activity is carried out has changed from period 1 to 2, as shown by the expansion in input use from X_1 to X_2. Comparing points E and G, we can measure the scale effects of this expansion by the ratio of the proportionate increase in output to the proportionate increase in input use to get the index of production scale effect (ISE) as follows:

$$ISE = \left(\frac{DG}{AE}\right) \Big/ \left(\frac{OD}{OA}\right) = \frac{DG}{DF}$$

Since the production function is concave as we move from E to G, the productivity contribution of the expansion is negative. The expansion raises output from E to G rather to F.

The last productivity change component, consisting of the move from point G to point I, measures the contribution of technological change (ITC) or the shift in the production technology from $F^1(X)$ and $F^2(X)$. The index measuring this is:

$$ITC = \frac{DI}{DG}$$

After combining (multiplying) the above three components into a productivity index, we get the total factor productivity index:

$$\begin{aligned} TFP &= ITEC \ x\ ISE \ x\ ITC \\ &= \left(\frac{DH}{AB}\right) \Big/ \left(\frac{OD}{OA}\right) \\ &= \left(\frac{Q_2}{Q_1}\right) \Big/ \left(\frac{X_2}{X_1}\right) \end{aligned}$$

This last result, which is also equal to the ratio of productivity values in period 2 and 1 or DH/DK, is the conventional measure of productivity obtained by comparing the index of outputs to inputs.

The empirical analysis in this study uses *input-oriented* measures of efficiency and productivity because these measures are more meaningful in the presence of undesirable or pollutant outputs. Comparison of results from analyses with and without undesirable outputs is also facilitated if input-based measures are used. The TFP decomposition results illustrated above can also be shown using input based measures. The input-oriented Farrell (1957) measure of technical efficiency would be given by the reciprocal of the ratio of actual input use to the minimum amount of input that can produce the same output level under the prevailing technology. In the diagram, this minimum input level would be identified by moving horizontally from the observed point of operation to the production function. Thus, the technical efficiency levels in period 1 and 2 are OS/OA and OR/OD, respectively. The productivity effects associated with the scale expansion of output from Q_1 to Q_2, is measured by ratio of (Q_2/ Q_1) to (OT/OS). The third component, technical progress, would be measured by the proportionate reduction in input use made possible by operating at point N rather than point L to produce Q_2, i.e. OT/OR. The product of the three input-oriented indexes of technical efficiency change, scale effects, and technical progress equals the TFP measure of output index divided by the input index described above.

The simple example above indicates that observed differences in productivity may be explained by factors that have different managerial and policy implications. As a result, the importance of employing empirical methods that allow for distinguishing between these components must be emphasized. In practice, however, the record of empirical research has been far from ideal in this regard.

2.2.2 Approaches to Productivity Measurement

Although the definition and measurement of technological change and technical efficiency share a common methodological basis (such as the production function), empirical analyses of productivity growth have evolved along two largely independent lines (Nishimuzi and Page 1982, Grosskopf 1993). The nonfrontier or traditional approaches to productivity measurement generally (implicitly) assume that observed productive activities are best practice or frontier activities. Thus technical change and total factor productivity are used synonymously in this literature (Nishimuzi and Page 1982, Grosskopf 1993). On the other hand, the frontier or efficiency literature is based on Farrell's (1957) concept of frontier or "best practice" production function against which variations in TFP of individual observations are measured.[3] More often than not, in both the nonfrontier and the frontier literatures, estimation and interpretation is simplified by employing the assumption of constant returns to scale to rule out productivity effects arising from changes in scale of production.

2.2.2.1 Nonfrontier Approaches

Two general approaches to productivity measurement have commonly been used in the nonfrontier literature: the index number (growth accounting) approach and the econometric approach. Extensive surveys of the techniques employed under in this literature are available in Diewert (1989), Link (1987), and Antle and Capalbo (1988).

Under the index number approach, productivity is simply measured through the residual growth in outputs that is not explained by growth in inputs. There is an endless number of index number formulas that the analyst can choose from for aggregating inputs and outputs. These include such widely known indexes as the Laspeyres and Paasche indexes as well as the Fisher's ideal and Tornqvist indexes that are commonly used in contemporary productivity analysis.

The greatest advantage of the index number approach is that it does not suffer from degrees of freedom problems. It can be applied when econometric estimation is infeasible, regardless of the number of inputs and outputs or the number of observations. However, the choice of a particular index number formula implies implicit assumptions about the nature of the underlying production technology (Diewert 1976). Index number approaches typically assume constant returns to scale and the absence of technical inefficiency or changes thereof. Thus residual measures of productivity calculated from index numbers include the effects of technical change and other factors such as changes in the degree of productive efficiency and output scale effects, as indicated above. Moreover, index numbers do not account for measurement or sampling errors, and statistical approaches cannot be employed to assess their reliability.

Econometric approaches to nonfrontier productivity measurement are based on explicit specification and econometric estimation of the structure of the technology. Primal (commonly production functions) or dual (cost or profit function) representations of the production technology are used. In contrast to the index number approach, technological change is assumed to be a smooth function of time that can be represented by the inclusion of a time trend variable as a proxy for the state of the technology. The shift in the function, as measured by the derivative of the estimated function with respect to the time trend variable, is used as a measure of technical change.

A shortcoming of the use of the production function is that output is required to be scalar. On the other hand, the extension of cost and profit function analysis to accommodate multiple output production processes is straight forward. In addition, the derivation of optimal input demand and/or output supply functions is less complicated under the dual approach (Diewert 1974). However, the use of dual functions implies the imposition of cost minimization or profit maximization behavioral assumptions. The justification for the use of approaches which impose such behavioral assumptions on aggregate data is not clear (Pope 1982).

Although it is theoretically possible to explicitly model productive efficiency using econometric approaches, most traditional productivity studies ignore inefficiency. Many studies following the econometric approach also assume constant returns to scale to simplify analysis or for degrees of freedom reasons; therefore, the distinction is not always made between technical change and output expansion effects even when econometric techniques are employed. Furthermore, different separability assumptions are commonly imposed on the underlying technology as outputs and inputs are aggregated into indexes to facilitate econometric estimation and save degrees of freedom.

2.2.2.2 Frontier Approaches

The modern literature on frontier analysis or efficiency measurement began with the work of Farrell (1957). Farrell proposed specific measures of technical and allocative efficiency within the context of linearly homogenous production technologies. The study of frontiers has advanced in the four decades following Farrell's path breaking work. For extensive surveys of the history and techniques of the literature see Coelli, Rao and Battese (1998), Lovell (1993), Schmidt (1986), and Førsund, Lovell, and Schmidt (1980).

Techniques employed in the efficiency literature include econometric, nonparametric and goal programming approaches (Lovell 1993).[4] The econometric approach involves the use of econometrically estimated single and multiple equations models, including models based on panel data. An increasingly popular econometric approach consists of the stochastic frontier or composed error models introduced by Aigner, Lovell and Schmidt (1977) and Meeusen and van den Broeck (1977).

The nonparametric techniques used in efficiency analysis include such currently popular approaches as data envelopment analysis (DEA). DEA involves the construction of a nonparametric piece-wise frontier using mathematical programming. The DEA frontier is equivalent to the inner nonparametric bound explored in the economics literature by Varian (1984) and others based on nonparametric tests of regularity conditions.[5] Nonparametric frontier techniques are discussed in more detail in Chapter 4.

Goal programming approaches to efficiency analysis involve the estimation of parametric deterministic frontiers using mathematical programming. This approach was initiated by Aigner and Chu (1968) and has been used in several studies since then (Lovell 1993). The technique is discussed in more detail later; it is also used to estimate the parameters of distance functions in this and the next chapter.

2.2.2.3 Integrated Approaches

So far the discussion has focused on studies that deal with productivity measurement in the traditional sense, without account of efficiency changes, and on efficiency investigations focusing on cross-section observations. In the last fifteen years, however, some studies have attempted to measure productivity in ways that allow for the distinction between technical efficiency and technological change. These integrated studies have used both parametric and nonparametric techniques. Nishimuzi and Page (1982) were the first to propose a method for analyzing technical change simultaneously with efficiency change. Their study defines total factor productivity as the sum of change in technical efficiency and technological progress; the study estimated a deterministic translog production frontier using the Aigner and Chu (1968) mathematical programming technique. Perelman and Pesteau (1988) apply a similar productivity measure using a production function estimated using corrected ordinary least squares. Perelman (1995) applies this productivity measure using a stochastic frontier production function. Fare *et al* (1989) and Fare *et al* (1994) have employed nonparametric (DEA) frontiers to compute the Malmquist productivity index which combines both the technological change and efficiency change components of productivity growth.

This study uses input distance functions as well as index number procedures to analyze technical change and productivity growth in the Canadian pulp and paper industry during the period from 1959 to 1994. Distance functions have features that make them especially attractive for technical change and productivity analysis as the following section shows.

2.3 Distance Functions

Input distance functions were introduced into economics by Ronald Shephard in a 1953 book that is widely known for other more popular reasons, including the commonly used lemma named after him. Although Shephard (1970) continued to explore the properties and potential applications of input distance and output distance functions in his later work, distance functions remained less known and less used tools in empirical economic analysis. The last decade and a half has, however, been a period of rising interest in the use of distance function methods. There are at least two important factors behind this increasing popularity. One is the introduction into the literature, by Caves, Christensen and Diewert (1982a), of new output- and input-oriented Malmquist productivity indexes that are defined in terms of output and input distance functions, respectively. The second is the numerous works on input and output distance functions of Rolf Fare and associates (e.g. Fare 1988; Fare and Grosskopf 1994; Fare and Primont 1995).

Distance functions are more versatile and more general than production functions. Like cost and profit functions, distance functions are convenient for handling multiple output, multiple input technologies. Unlike cost and profit functions, the use of distance functions does not require data on input or output prices, or any implicit or explicit assumptions regarding economic behaviour. Moreover, distance function values are directly related to the most frequently used Farrell measures of technical efficiency. Malmquist (productivity, output, or input) indexes are defined in terms of distance functions. Under common regularity conditions, distance functions provide a complete representation of the technology; and they are dual to cost, profit or other representations of production technology.[6]

2.3.1 Definition and Properties

In the case of a production technology using N inputs to produce M outputs, the input distance function (Shephard 1953, 1970; Fare and Primont 1995)

$$D : R_+^N \times R_+^M \rightarrow R_+ \cup \{+\infty\}$$

is defined as follows, after the introduction of a time trend in our particular case to capture

$$D(u,x,t) = \sup_\theta \left\{ \theta : \left(u, \frac{x}{\theta}\right) \in Y(t), \quad \theta \in R^+ \right\} \qquad (2.1)$$

technological change,

where: x and u are the input and output vectors; t is the time trend variable; and Y(t) is the technology (or production possibility) set at time t. In other words, the value of the input distance function measures the maximum factor by which the input vector can be proportionally deflated, given the output vector and the state of the production technology.

Since by definition the input distance function measures the maximal proportion by which the vector of inputs can be reduced, its inverse provides an input-based measure of Farrell (1957) technical efficiency, i.e.

$$TE_x(u,x,t) = \frac{1}{D(u,x,t)} \qquad (2.2)$$

In other words, $(1\text{-}TE_x)$ measures the proportion by which costs would be reduced by improving productive efficiency, without reducing output. An input distance function value of greater than unity indicates that the firm is inefficient. An input distance function value of unity indicates that the firm is operating on the technology frontier.

The distance function has the following properties: it has a finite value[7] for $u \geq 0$; it is an increasing continuous function of x for $u \in R^{M}_{+}$; it is concave and homogeneous of degree one in x; it is decreasing,[8] upper semi-continous, and quasi-concave function of u. If inputs are freely disposable,[9] the input distance function provides a complete characterization of the production technology.

We can define technical efficiency and technical progress in terms of output-enhancement or input-saving and measure productivity growth accordingly. The two measures can be related through the returns to scale parameter. And they are equal when the technology is characterized by constant returns to scale. We will focus on input-based measures of productivity in this study for the reasons mentioned previously.

Our input-oriented measure of technical change is defined as the rate at which inputs can be proportionally decreased over time without change in output levels. This rate is equal to

$$TC_x(u,x,t) = \left(\frac{\partial \ln \zeta}{\partial t}\right)\Bigg|_{D(u,\zeta x,t)=1}$$

where ζ is a scalar representing an equiproportionate change in the input vector x. This measure reduces to a convenient form, specifically, the derivative of the distance function with respect to time,[10] i.e.

$$TC_x(u,x,t) = \left(\frac{\partial D(u,x,t)}{\partial t}\right) \qquad (2.3)$$

The alternative output-based measure of technical change measures the rate at which all outputs could be increased over time without any change in the vector of inputs used, i.e.

$$TC_u(u,x,t) = \left(\frac{\partial \ln \xi}{\partial t}\right)\Bigg|_{D(\xi u,x,t)=1} \qquad (2.4)$$

where ξ is a scalar representing the proportion by which the output vector is changed. By definition, TC_u is equal to the product of the input-based measure TC_x and the returns to scale measure (RTS). The latter can be computed from the following formula:

$$RTS(u,x,t) = \left(\frac{\partial \ln \xi}{\partial \ln \zeta}\right)\Bigg|_{D(\xi u,\zeta x,t)=1} = \frac{-\left(\partial D(.) / \partial \ln \zeta\right)}{\left(\partial D(.) / \partial \ln \xi\right)} = \frac{-(\nabla_x D(.)x)}{(\nabla_u D(.)u)} = \frac{-1}{(\nabla_u D(.)u)} \qquad (2.5)$$

The first equality in (2.5) follows from the definition of returns to scale as the equiproportionate change in outputs resulting from an equiproportionate change in inputs. The second and third equalities follow, respectively, from applications of the implicit function rule and the chain rule for differentiation. The linear homogeneity in inputs of the input distance function implies the fourth equality.

2.3.2 Functional Form

Flexible functional forms provide a second order approximation to the unknown technology. The flexible translog functional form (Christensen, Jorgenson and Lau 1973) was chosen for the input distance function:

$$
\begin{aligned}
\ln\ D(u,x,t) \quad = {} & \alpha_o + \sum_{n=1}^{N} \alpha_n . \ln x_n + \sum_{m=1}^{M} \beta_m . \ln u_m \\
& + (0.5) \sum_{n=1}^{N} \sum_{n'=1}^{N} \alpha_{nn} .. \ln x_n . \ln x_n . \\
& + (0.5) \sum_{m=1}^{M} \sum_{m'=1}^{M} \beta_{mm} .. \ln u_m . \ln u_m . \qquad (2.6) \\
& + (0.5) \sum_{n=1}^{N} \sum_{m=1}^{M} \gamma_{nm} . \ln x_n . \ln u_m \\
& + \alpha_t . t + (0.5) . \alpha_{tt} . t^2 \\
& + \sum_{n=1}^{N} \alpha_{nt} . t . \ln x_n + \sum_{m=1}^{M} \beta_{mt} . t . \ln u_m
\end{aligned}
$$

where: *n* indexes the vector of inputs such that the subscript numbers 1,2,...,7 represent, respectively, energy, wood residue, pulpwood, non-wood materials, production labour input, administration workers, and capital; *m* indexes the output vector of the firm such that the subscripts 1,2,3 and 4 represent wood pulp, newsprint, paper other than newsprint, and paperboards and building boards, respectively; and *t* denotes time trend.

2.3.3 Estimation of Parameters

The parameters of the distance function can be estimated either econometrically or using mathematical programming. Both estimation methods have their own strengths and limitations. Econometric estimation was not possible for this study because of the short length of the time series data that was available, compared to the number of model parameters to be estimated. Mathematical programming methods were used to estimate the parameters of the input distance function in equation (2.6).

Mathematical programming (also known as goal programming) methods for the stimation of parameter values were first employed by Aigner and Chu (1968) to estimate production function parameters for efficiency analysis. The method has been used in different efficiency and productivity studies since then. See Lovell (1993) on this. Recently Fare *et al* (1993) and Coggins and Swinton (1995) employed linear programming to estimate output distance function parameters.

The estimation problem was formulated in the form of the following linear programming problem. The objective in the problem is to choose the set of parameter estimates that minimizes the sum of deviations of the values of the distance function from unity. Monotonicity, homogeneity and symmetry conditions are imposed as constraints. An additional constraint imposed on the problem is the requirement that the value of the input distance should be equal to or greater than unity for all the 36 observed input output combinations. That is, the estimation takes the following form:

$$Minimize_{(\alpha,\beta,\gamma)} \sum_{t=1}^{36} \ln D(u,x,t) \qquad (LP1)$$

Subject to the following constraints:

$$\ln D(u,x,t) \geq 0, \quad t = 1,\dots,36 \qquad (C1)$$

$$\frac{\partial \ln D(u,x,t)}{\partial x_n} \geq 0, \quad t = 1,\dots,36,\ n = 1,\dots,7 \qquad (C2)$$

$$\frac{\partial \ln D(u,x,t)}{\partial u_m} \leq 0, \quad t = 1,\dots,36,\ m = 1,\dots,4 \qquad (C3)$$

$$\sum_{n=1}^{7} \alpha_n = 1 \qquad (C4a)$$

$$\sum_{n=1}^{7} \alpha_{nn'} = 1, \quad n' = 1,\dots,7 \qquad (C4b)$$

$$\sum_{n=1}^{7} \gamma_{nm} = 0, \quad m = 1,\dots,4 \qquad (C4c)$$

$$\sum_{n=1}^{7} \alpha_{nt} = 0, \qquad (C4d)$$

$$\alpha_{nn'} = \alpha_{n'n}, \quad n, n' = 1,\dots,7 \qquad (C5a)$$

$$\beta_{mm'} = \beta_{m'm}, \quad m, m' = 1,\dots,4 \qquad (C5b)$$

The first set of constraints (C1) ensures that the estimated technology includes the observed input output combinations as feasible. The second set of constraints (C2) imposes the monotonicity condition that the distance function be non-decreasing in inputs, while the third set of constraints (C3) requires that the function be a non-increasing function of outputs. The remaining set of constraints ensure the linear homogeneity of the input distance function with respect to inputs (C4) and the symmetry conditions for the translog function (C5).

In other words, the parameter estimation for the input distance function without pollutant outputs is carried out by minimizing the sum of deviations from unity subject to 472 constraints. These are 36 feasibility constraints; 396 monotonicity constraints relating to inputs (252) and outputs (144); 13 linear homogeneity conditions, and 27 translog symmetry restrictions. Despite its size, the programming problem is linear. A GAMS program was written to compute the parameter estimates by solving this linear programming problem.

The estimation procedures employed here are very similar to those in Fare et al (1993) and Coggins and Swinton (1995). The difference is that we have imposed monotonicity conditions relating to inputs in addition to those relating to outputs. Moreover, this analysis includes technical change.

2.4 Malmquist Indexes

Productivity estimates obtained using index number formulas such as the Tornqvist index reflect the effects of output scale changes in addition to technical change and changes in the degree of productive efficiency. To render index number estimates comparable to those obtained from the input distance function analysis discussed above, the former should be decomposed into output expansion effects and a residual productivity growth component. This is accomplished using a proposition due to Caves, Christensen and Diewert (1982a) for relating Malmquist and Tornqvist productivity indexes described below.

Caves, Christensen and Diewert (1982a) introduced a new productivity index defined in terms of distance functions. However, they treated their new (Malmquist) productivity index as a theoretical index and showed how the Tornqvist index can be derived from it. For two firms, *k* and *l*,[11] with output -input vectors (u^k,x^k) and (u^l,x^l) and production technologies given by the input distance functions $D^k(.)$ and $D^l(.)$, respectively, their Malmquist input based productivity index for comparing the productivity of *l* to that of *k* is defined as:

$$M(x^l,x^k,u^l,u^k)=\left[\left(\frac{D^k(u^k,x^k)}{D^k(u^l,x^l)}\right)\cdot\left(\frac{D^l(u^k,x^k)}{D^l(u^l,x^l)}\right)\right]^{\frac{1}{2}} \qquad (2.7a)$$

M is a geometric mean of the two Malmquist input-based productivity indexes, each defined with a different reference technology. If the firms are both technically efficient, the first ratio inside the square brackets in (2.7a) measures the minimal inflation factor such that the inflated input for firm *l* and the output vector of firm *l* lie on the production surface of firm *k*. This ratio is higher than one if and only if firm *l* has a higher productivity level than firm *k*. The second ratio measures the maximal input deflation factor such that the deflated input from firm *k* and the output vector of *k* lie on the production surface of *l*. This again is above unity if and only if *l* is more productive than *k*.

The Malmquist index is related to the commonly used Tornqvist productivity index by the following theorem due to Caves, Christensen, and Diewert (1982a):

> *If firms k and l have translog input distance functions, with identical second order coefficients, then the Malmquist input based productivity index M defined above is a product of a scale factor and the ratio of the Tornqvist index for comparing the outputs of k and l to the Tornqvist index for comparing the inputs of k and l,* i.e.

$$\begin{aligned}\ln M(x^l,x^k,u^l,u^k)= \quad & (0.5)\sum_{m=1}^{4}\left[\left(\frac{r_m^k u_m^k}{r^k u^k}+\frac{r_m^l u_m^l}{r^l u^l}\right)\left(\ln u_m^l-\ln u_m^k\right)\right] \\ & -(0.5)\sum_{n=1}^{7}\left[\left(\frac{p_n^k x_n^k}{p^k x^k}+\frac{p_n^l x_n^l}{p^l x^l}\right)\left(\ln x_n^l-\ln x_n^k\right)\right] \qquad (2.8) \\ & +(0.5)\sum_{m=1}^{4}\left\{\left[\left(\frac{1}{\varepsilon^k}-1\right)\left(\frac{r_m^k u_m^k}{r^k u^k}\right)+\left(\frac{1}{\varepsilon^l}-1\right)\left(\frac{r_m^l u_m^l}{r^l u^l}\right)\right]\left(\ln u_m^l-\ln u_m^k\right)\right\}\end{aligned}$$

where: r and p denote, respectively, output and input price vectors; and ε^k and ε^l are the returns to scale values for firms *k* and *l*, respectively. The first two lines in the equation above are equal to the Tornqvist index for comparing the productivity of firm *l* to that of firm *k*. The third line represents the scale factor that constitutes the difference between the Malmquist and Tornqvist indexes. If the production technology is characterized by constant returns to scale, this scale factor vanishes. In other words, the above result from Caves, Christensen and Diewert (1982a) shows that the Tornqvist index is superlative in a more general sense than was shown by Diewert (1976).

Although not recognized by Caves, Christensen and Diewert (1982a) at the time, the formulation of the Malmquist index in terms of distance functions (which are related to Farrell measures of efficiency) leads to a straight forward calculation of the index from parametric as well as nonparametric representations of the technology. Following Fare *et al* (1989), the Malmquist index in (2.7) can be decomposed into efficiency and technical change components as follows:

$$M(x^l,x^k,u^l,u^k)=\left[\frac{D^k(u^k,x^k)}{D^l(u^l,x^l)}\right]\left[\left(\frac{D^l(u^l,x^l)}{D^k(u^l,x^l)}\right)\cdot\left(\frac{D^l(u^k,x^k)}{D^k(u^k,x^k)}\right)\right]^{\frac{1}{2}} \qquad (2.7b)$$

This is accomplished by first multiplying the term under the square root sign in equation (2.7a) by $[D^l(u^l,x^l)/ D^k(u^k,x^k)]^2$ and then multiplying the whole right hand side by $[D^k(u^k,x^k)/ D^l(u^l,x^l)]$ to preserve equality. The first ratio measures the technical efficiency of firm *l* relative to *k*. The second term is the technical change component of the Malmquist index computed as the geometric mean of the shift in the technology measured on the two observed output levels instead of at one point. In terms of the production changes illustrated in Figure 2.1 above, the two components of the Malmquist index can be computed as follows, after assuming that firm *k* is operating at point B and has the technology indicated by $F^1(X)$ whereas firm *l* is the one producing at point H while facing the production technology $F^2(X)$:

$$\mathit{Efficiency Component} = \left[\frac{D^k(u^k,x^k)}{D^l(u^l,x^l)}\right] = \left(\frac{OA}{OS}\right) \Big/ \left(\frac{OD}{OR}\right)$$

$$\begin{aligned}\mathit{Technical\ Change} &= \left[\left(\frac{D^l(u^l,x^l)}{D^k(u^l,x^l)}\right)\cdot\left(\frac{D^l(u^k,x^k)}{D^k(u^k,x^k)}\right)\right]^{\frac{1}{2}} \\ &= \left[\left(\left(\frac{OD}{OR}\right)\Big/\left(\frac{OD}{OT}\right)\right)\left(\left(\frac{OA}{OV}\right)\Big/\left(\frac{OA}{OS}\right)\right)\right]^{\frac{1}{2}} \\ &= \left[\left(\frac{OT}{OR}\right)\left(\frac{OS}{OV}\right)\right]^{\frac{1}{2}}\end{aligned}$$

Obviously, the Malmquist index includes total factor productivity change due to technical change and technical efficiency changes, to the exclusion of production scale effects. The Malmquist index can be calculated from nonparametric technology representations such as DEA (e.g. Fare *et al* 1989) or from parametrically specified technologies (e.g. Nishimuzi and Page 1982; Perelman 1995).

In this study, the proposition of Caves, Christensen and Diewert (1982a) discussed above was used to derive Malmquist index M from the Tornqvist productivity index, using returns to scale estimates obtained from the estimated input distance function. These were compared to Malmquist indexes calculated from the distance function. For the derivation based on input distance function results, the growth rate in the Malmquist index in (2.7b) was computed as follows:

$$\begin{aligned}\ln M(x^{t+1},x^{t},u^{t+1},u^{t}) \quad &= \left[\ln D(u^{t},x^{t},t)-\ln D(u^{t+1},x^{t+1},t+1)\right] \\ &+\frac{1}{2}\left[\frac{\partial D(u^{t},x^{t},t)}{\partial t}+\frac{\partial D(u^{t+1},x^{t+1},t+1)}{\partial t}\right]\end{aligned} \qquad (2.9)$$

The first term in square brackets measures the rate of improvement in technical efficiency between period t and t+1. The second term represents the estimated rate of technical change over that period obtained by averaging the technical change growth rates computed at t and t+1. This formula was employed by Nishimuzi and Page (1982) to approximate the Malmquist index growth rate based on their estimation results for a deterministic translog frontier. Perelman (1995) uses the formula to compute Malmquist indexes based on estimation results for a stochastic Cobb-Douglas frontier.

2.5 Results and Discussion

Outputs from the Canadian pulp and paper industry were categorized into four major groups: newsprint, paper other than newsprint, paperboards and building boards, and market (or net output of) wood pulp. Seven input categories were identified in this particular study. These include energy, wood residue, pulpwood, non-wood materials, production labour input, administration workers, and capital. The sample consists of time series data for the national pulp and paper industry covering the period from 1959 to 1994.

2.5.1 Input Distance Function Analysis

The parameter estimates for the input distance function in equation (2.6) are shown in Table 2.1. These estimates were obtained by minimizing the sum of deviations from unity, subject to the monotonicity (C2 and C3), the "feasibility" (C1), homogeneity (C4) and symmetry (C5) conditions described above. Curvature conditions of the input distance function were not imposed during the estimation because that turned the mathematical programming problem into a highly non-linear problem. Instead, the curvature conditions were tested for all the years in the sample period after the model was estimated. Concavity and quasi-concavity conditions were satisfied by the estimated input distance function for all the observations in the sample. The eigenvalues for the tests of concavity in inputs are reported in Table 2.2. The results from determinantal tests of quasi-concavity in outputs of the input distance function are reported in Table 2.3.

Estimated technical efficiency was less than 100 percent mainly during periods of macroeconomic recession, oil price hikes of early and late 1970s and periods of large capacity expansion and capacity underutilization. These include the macroeconomic recession periods of 1981-82 and 1989 caused by Central Bank of Canada's policy of monetary restraint. Other periods of estimated technical inefficiency include 1966, 1967, 1972, 1974, 1976, 1979 and 1986. The years 1966, 1967, 1971 and 1972 were periods of the largest expansions in the industry, when pulp and paper production capacity increased by 8.5, 6.6, 6.4 and 5.2 percent, respectively. Furthermore, the capacity utilization rates for 1966, 1967, 1972, 1974 and 1976 were also smaller than the sample average utilization rate of 89.3 percent according to industry statistics. The computed overall or sample average degree of technical efficiency is 99.6 percent. This high level of overall technical efficiency is partly due to the nature of the model in which only one producer (i.e. the national pulp and paper industry) is included and due to the nature of the input distance function parameter estimation which is based on the minimization of the sum of deviations from the frontier.

The production technology of the Canadian pulp and paper industry is characterized by increasing returns to scale (RTS). A mean returns to scale estimate of 1.27 was calculated for the sample period. Compared to returns to scale estimates from previous studies, the estimates obtained here appear to be lower and more consistent with the observation that many firms do exist in this industry. The estimated value from Sherif (1983) is 1.5. Martinello (1985) and Frank *et al* (1990) report returns to scale estimates of 2.0 and 1.79, respectively.

Input-based Malmquist productivity indexes were calculated from the distance function. The Malmquist indexes discussed above, include the effects of changes in productive efficiency and technical progress. Since the degree of productive or technical efficiency was high throughout the period, the sample average estimates of productivity growth reflect mainly the effects of technical change. The results are shown in Table 2.4.

Most of the productivity growth in the Canadian pulp and paper industry occurred in the periods after the 1981-82 recession. Productivity improved at an average annual rate of 0.99 percent in the 1980s. Growth was fastest in the period from 1990 to 1994, when productivity grew at the rate of 3.95 percent per year. On average, reductions in productivity occurred in the 1960s (-1.55 percent per year) as well as in the 1970s (-0.74 percent per year). Overall, estimates from the input distance function indicate that the productivity of the Canadian pulp and paper industry progressed at a rate of 0.19 percent per year over the period from 1959 to 1994.

A combination of factors contributed to the rapid improvement in productivity evidenced in the early 1990s. The first is the addition of a relatively large number of new pulp and paper mills. Nine new pulp mills commenced operation in the four year period from 1990 to 1993, compared to only six new start-ups in the entire 1980s. These new mills include giant mills like the Daishowa mill in Peace River, Alberta, and the Alberta-Pacific mill in Athabasca, Alberta. The addition of these two new mills with production capacities of 340 and 500 thousand metric tonnes of pulp per year in 1990 and in 1993 constituted, respectively, a 4.0 and a 5.3 percent expansion in the national market pulp production capacities. The industry also has four new paper mills (three of which were large) which started up in 1990 and 1991. The three large new newsprint mills[12] increased the national newsprint production capacity by 6.6 percent. Four large paper mills had also been added to the industry in 1986 and in 1989. The addition of 9 paper mills in the six year period from 1986 to 1991, as compared to only two new mills in the decade from 1976 to 1985, means a higher proportion of paper mills equipped with efficient and modern technologies in the early 1990s than in the previous decades. The second phenomenon that contributed to the rapid productivity growth in the early 1990s is the closure of a number of old mills. One pulp and eight paper mills closed down in this period. High cost or marginal mills exit the industry during periods of lower than anticipated price that may come in the wake of large expansions in capacity (McCubbin *et al* 1990).

The retardation in productivity in the 1970s is explained, at least partially, by the economic contractions resulting from the two oil crises. The rate of capacity utilization in the 1970s was lower than in any other decade covered in the study. The share of pollution abatement in total capital expenditure also rose substantially as a result of the introduction of new environmental regulations in the early 1970s. As the conventional measures used in this chapter include these abatement expenditures to costs without adding the benefits of the protection to the output measures, higher abatement expenditures have negative effect on productivity growth rates as measured in conventional ways.

The productivity decline in the 1960s is difficult to explain. One possible explanation is the rapid investment in capacity expansion and low capacity utilization in the decade. The overall or macroeconomic situation in that decade was encouraging. The capacity of the industry increased at 4.4 percent per year on average in the 1960s. The capacity utilization rate for this period was also lower than the sample average rate of utilization although it was higher than the rate for the 1970s. Detailed data on changes in the composition of the industry would have helped shed more light on the productivity trends in the 1960s. Unfortunately, we do not have information on individual mill expansion, exit or entry for the period before 1976. However, results from the other studies in this thesis indicate that productivity growth was higher in the 1960s than in the 1970s.

It is difficult to draw firm conclusions by comparing our results to those from other studies because of the differences in estimation methods, as well as differences in the nature and coverage of the data used in these studies. But rough comparisons of our results from the parametric input distance function approach to those from the studies using cost function approaches indicate the following. Our productivity growth estimate for the period from 1959 to 1977 (-1.2 percent per year) is similar to the –1.3 percent per year reported by Sherif (1983) for the period from 1957 to 1977. Our estimates for the 1963-1982 period (-0.97 percent) are much higher than the rate of –9.5 percent obtained by Martinello (1985) for the same period.

2.5.2 Index Number Analysis

2.5.2.1 Single Factor Productivity

Tornqvist index formulas were used to aggregate inputs and outputs. Then partial and total factor productivity measures were calculated. As indicated in reference to equation (2.8) above, the Tornqvist index for comparing the total factor productivity (TFP) of period $t+1$ to that of period t is given by:

$$\ln\left(\frac{TFP^{t+1}}{TFP^{t}}\right)= \quad (0.5)\sum_{m=1}^{4}\left[\left(\frac{r_m^t.u_m^t}{r^t.u^t}+\frac{r_m^{t+1}.u_m^{t+1}}{r^{t+1}.u^{t+1}}\right).\left(\ln u_m^{t+1}-\ln u_m^t\right)\right]$$

$$-(0.5)\sum_{n=1}^{7}\left[\left(\frac{p_n^t.x_n^t}{p^t.x^t}+\frac{p_n^{t+1}.x_n^{t+1}}{p^{t+1}.x^{t+1}}\right).\left(\ln x_n^{t+1}-\ln x_n^t\right)\right] \qquad (2.10)$$

The estimates of single factor productivities (SFP) are computed by taking the ratio of the Tornqvist output index to the index of the particular factor under consideration. For input *n*, for example, we have the following single factor productivity growth formula:

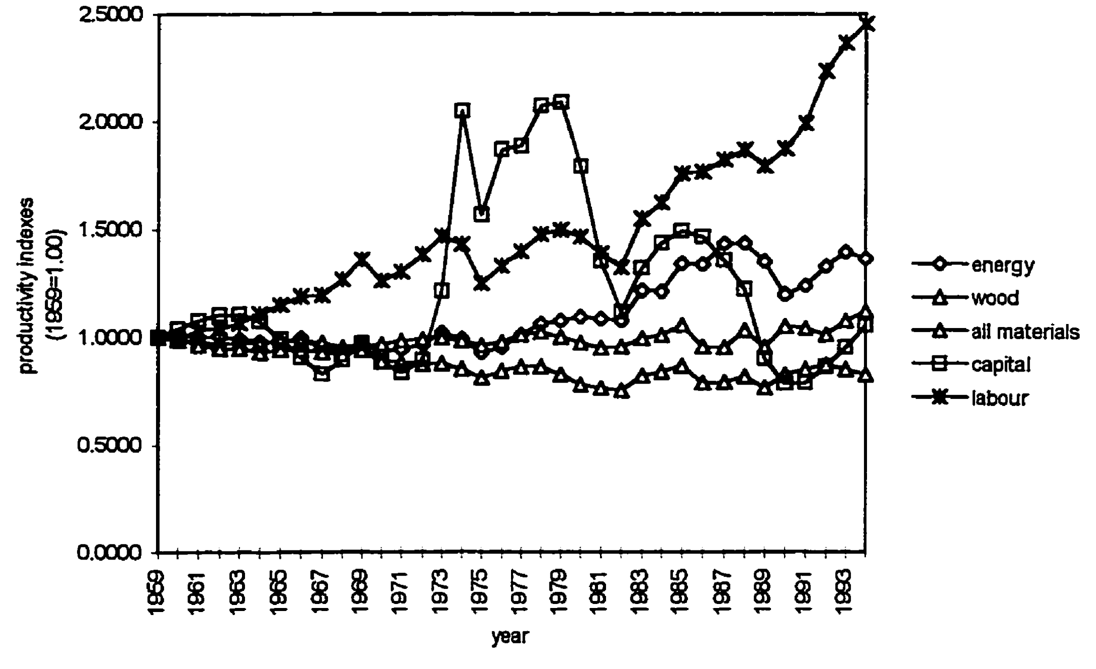
$$\ln\left(\frac{SFP_n^{\;t+1}}{SFP_n^{\;t}}\right)= \quad (0.5)\sum_{m=1}^{4}\left[\left(\frac{r_m^t.u_m^t}{r^t.u^t}+\frac{r_m^{t+1}.u_m^{t+1}}{r^{t+1}.u^{t+1}}\right).\left(\ln u_m^{t+1}-\ln u_m^t\right)\right]-\left(\ln x_n^{t+1}-\ln x_n^t\right) \qquad (2.11)$$

The results from these calculations are summarized in Table 2.5. Labour productivity, the most commonly used measure of single factor productivity, showed the fastest growth in the period from 1959 to 1994, growing at a rate of 2.64 percent per year. As a result, the productivity of labour was 152 percent above what it was in the beginning of the period. Growth in production labour productivity was fastest in the period from 1990 to 1994 (6.65 percent) and lowest in the 1970s when labour productivity grew at a rate of only 1.11 percent. Within the labour input category, the productivity of production labour grew at a rate of 2.83 percent during 1959-1994, higher than the rate of 2.07 percent for the productivity of administration workers. The productivity of pulpwood and energy also increased at average rates of 2.73 percent and 0.90 percent per year, respectively.

The productivity of wood residue showed the greatest decline (-5.66 percent per year), followed by that of non-wood materials and capital inputs which declined at the rates of -1.53

percent and -0.84 percent, respectively. The productivity of virgin fibre as a whole, however, increased at a positive rate of 0.3 percent, despite the fast decline in the productivity of wood residue. The productivity of all materials, on the other hand, showed a decline at the rate of -0.57 percent per year. See Figure 2.2 for the single factor productivity indexes.

Figure 2.2
Single Factor Productivity Indexes: Canadian Pulp and Paper Industry, 1959-1994

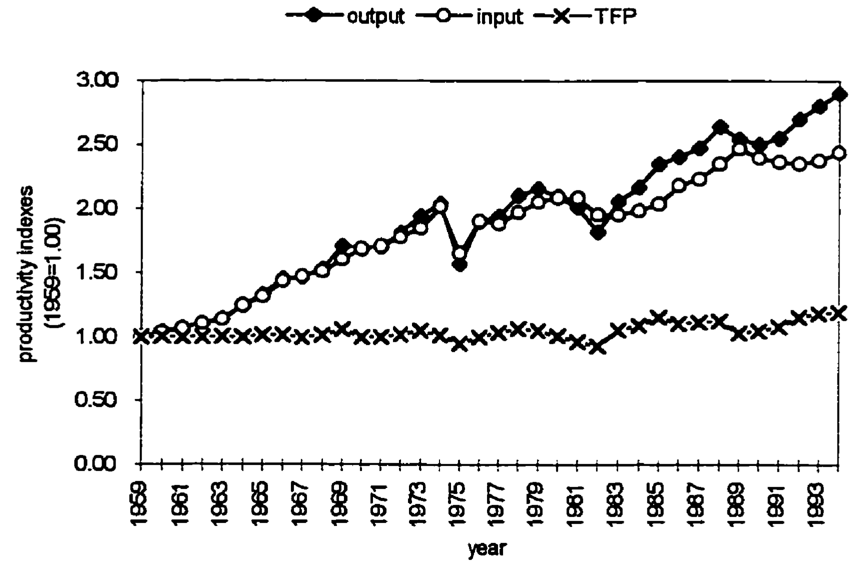


2.3.3.2 Total Factor Productivity

When a multi-factor or total factor productivity (TFP) measure is used instead of the single factor productivity measures, the results are dramatically different. Aggregate input use and output grew at very close rates during most of the 1960s. As a result, there was a very small productivity improvement from 1959 to 1969. In 1969, productivity stood at only 104.6 percent of what it was in 1959.

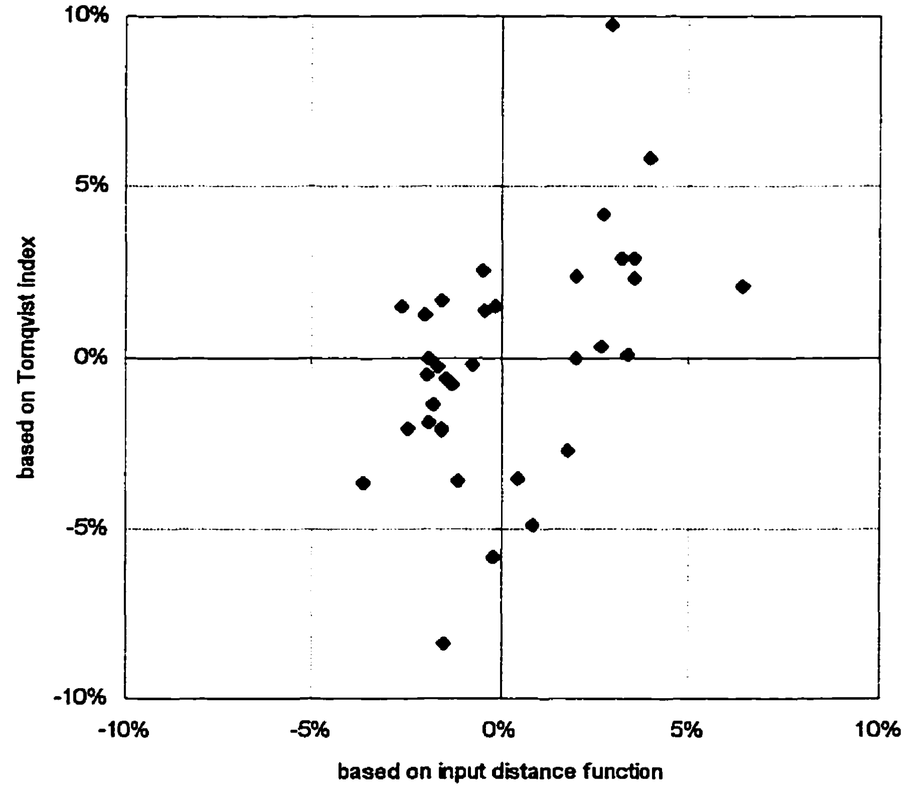
In the 1970s and 1980s, TFP generally declined. The fall in TFP (at an average rate of -0.22 percent) in the 1970s was primarily due to reductions in productivity in 1974, 1975 and also 1979. This TFP decrease continued in 1980-1982 and this, together with the TFP decreases that occurred in 1986 and 1989, resulted in an average TFP growth rate of -0.38 percent for the 1980s. However, in the period from 1990 to 1994, TFP increased at a rate of 3.14 percent. Overall, the productivity of the industry as measured by the Tornqvist index had been growing at an average rate of 0.41 percent and as a result the productivity of the industry in 1994 was only 15.3 percent above what it was 36 years earlier in 1959. Possible reasons for the variation in productivity growth rates over time were discussed above in connection with the results from the input distance function.

Figure 2.3
Output, Input and Total Productivity Indexes: Canadian Pulp and Paper Industry, 1959-1994



The Caves, Christensen and Diewert (1982a) theorem in (2.8) relating Malmquist and Tornqvist indexes was employed to adjust estimates from the latter by removing output scale effects. These productivity growth estimates from the index number approach are compared with the same estimates from the input distance function in Figure 2.4.

Figure 2.4
Input-Based Malmquist Productivity Index Growth Rates for the Canadian Pulp and Paper Industry, 1959-1994: Distance Function vs Tornqvist Index Based Results



Both approaches give similar productivity trends for most of the periods covered in the study, i.e. most points lie on the first and third quadrants in the diagram. However, after controlling for output expansion effects, the average productivity growth estimate obtained from the Tornqvist index was only -0.06 percent per year. These results corroborate previous findings which indicated that most of the productivity growth as measured by TFP index formulas was due to output scale effects. For example, Frank *et al* (1990) calculate the average Tornqvist productivity growth rate for the Canadian pulp and paper industry over the period from 1963 to 1984 to be 1.2 percent per year. But they attribute only about a quarter of that (0.32%) to technical change after adjustment for scale effects.

2.6 Summary and Conclusion

This study attempted to analyze productivity in the Canadian pulp and paper industry using input distance functions and index number procedures. The input distance function offers a framework within which efficiency and productivity can be measured in an integrated way. The study also extended the existing productivity literature on the industry by using a revised and extended data set covering the period from 1959 to 1994. The superlative Tornqvist index formula was used to compute output, input, single factor and total factor productivity indices. The input distance function was specified as a translog form. The parameters of the function were then estimated by linear programming methods in which the sum of deviations of distance function values from unity were minimized, subject to monotonicity, homogeneity and symmetry conditions.

Single factor productivity estimates indicate that the productivity of wood residue, non-wood materials and capital inputs declined. This fall in productivity was highest for wood residue input, the use of which had increased twenty-fold in the period from 1959 to 1994. Because of improvements in the productivity of pulpwood, however, the productivity of wood (virgin fibre) inputs increased at the rate of 0.30 percent per year. The productivity of energy increased at the rate of 0.09 percent. The highest increase occurred in the productivity of labour, which grew at a rate of

2.64 percent per year. As a result, labour employed in the Canadian pulp and paper industry was 2.5 times more productive in 1994 than it was in 1959.

The total factor productivity of the industry, on the other hand, showed little or no signs of change in the period from 1959 to 1994. Improvements in efficiency and technical change occurred at an average annual rate of 0.19 percent according to the input distance function estimates. According to the comparable Malmquist index growth rate derived from the Tornqvist index by removing output scale effects, productivity declined at an average annual rate of -0.06 percent. Productivity growth was negative or very weak in the 1960s, 1970s and 1980s. In the period from 1990 to 1994, however, the productivity of the industry showed very strong positive trends because of a favourable change in the mill composition as a result of the closure of many old mills and the entry of new and modern pulp and paper mills.

Results from the distance function analysis show that the production technology of the Canadian pulp and paper industry is characterized by modest increasing returns to scale. An average returns to scale value of 1.27 was calculated. This estimate is lower and also arguably more reasonable than the higher estimates (ranging from 1.5 to 2.00) reported by several previous studies. The results show that most of the gains in productivity as measured by widely used index number procedures are attributable to output expansion effects rather than to technical progress or improvements in productive efficiency.

The efficiency and productivity estimates derived and discussed in this chapter are conventional measures in the sense that they do not take into account changes in the effects of the industry on the environment. In the next chapters, we will look at models and productivity measures that incorporate undesirable or pollutant outputs along with marketed inputs and outputs.

Table 2.1 Parameter Estimates for the Translog Input Distance Function: The Canadian Pulp and Paper Industry, 1959-94[13].

α_1	-0.099	α_{23}	-0.057	α_{77}	-0.078	γ_{31}	-0.326	γ_{74}	0.263
α_2	1.880	α_{24}	1.051	β_{11}	0.298	γ_{32}	1.291	α_T	-0.564
α_3	-5.121	α_{25}	-0.158	β_{12}	0.349	γ_{33}	-0.914	α_{TT}	0.009
α_4	3.897	α_{26}	0.083	β_{13}	-0.929	γ_{34}	-0.581	α_{1T}	0.039
α_5	-1.223	α_{27}	-0.294	β_{14}	0.186	γ_{41}	-0.540	α_{2T}	-0.031
α_6	-0.861	α_{33}	0.649	β_{22}	0.527	γ_{42}	-0.871	α_{3T}	0.063
α_7	2.528	α_{34}	-0.669	β_{23}	-0.236	γ_{43}	0.475	α_{4T}	-0.075
β_1	-2.788	α_{35}	-1.103	β_{24}	-0.829	γ_{44}	-0.071	α_{5T}	0.002
β_2	-6.770	α_{36}	-0.084	β_{33}	-0.664	γ_{51}	1.358	α_{6T}	0.002
β_3	4.987	α_{37}	0.047	β_{34}	1.158	γ_{52}	-1.399	α_{7T}	0.000
β_4	1.129	α_{44}	-0.504	β_{44}	-0.061	γ_{53}	-0.280	β_{1T}	0.054
α_{11}	-0.792	α_{45}	-0.398	γ_{11}	-0.850	γ_{54}	0.354	β_{2T}	0.043
α_{12}	-0.030	α_{46}	-0.235	γ_{12}	1.378	γ_{61}	0.043	β_{3T}	-0.050
α_{13}	1.216	α_{47}	0.582	γ_{13}	-0.196	γ_{62}	-0.138	β_{4T}	-0.070
α_{14}	0.174	α_{55}	1.442	γ_{14}	0.157	γ_{63}	0.211	α_0	17.983
α_{15}	-0.236	α_{56}	0.332	γ_{21}	0.097	γ_{64}	-0.149		
α_{16}	-0.069	α_{57}	0.122	γ_{22}	0.370	γ_{71}	0.218		
α_{17}	-0.264	α_{66}	0.088	γ_{23}	0.714	γ_{72}	-0.632		
α_{22}	-0.595	α_{67}	-0.115	γ_{24}	0.027	γ_{73}	-0.010		

Table 2.2 Test Results for Concavity in Inputs of the Estimated Input Distance Function[14]

year	EIGENVALUE1	EIGENVALUE2	EIGENVALUE3	EIGENVALUE4	EIGENVALUE5	EIGENVALUE6	EIGENVALUE7
1959	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1960	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1961	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1962	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1963	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1964	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1965	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1966	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1967	-0.003	0.000	0.000	0.000	0.000	0.000	0.000
1968	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1969	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1970	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1971	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1972	-0.001	0.000	0.000	0.000	0.000	0.000	0.000
1973	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1974	-0.002	0.000	0.000	0.000	0.000	0.000	0.000
1975	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1976	-0.004	0.000	0.000	0.000	0.000	0.000	0.000
1977	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1978	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1979	-0.001	0.000	0.000	0.000	0.000	0.000	0.000
1980	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1981	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1982	-0.002	0.000	0.000	0.000	0.000	0.000	0.000
1983	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1984	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1985	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1986	-0.001	0.000	0.000	0.000	0.000	0.000	0.000
1987	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1988	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1989	-0.002	0.000	0.000	0.000	0.000	0.000	0.000
1990	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1991	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1992	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1993	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1994	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table 2.3 Determinantal Test of Quasi-Concavity in Outputs of Estimated Input Distance Function[15]

	Determinants of the principal minors of the bordered Hessian:			
year	BH1	BH2	BH3	BH4
1959	-0.117	0.000	0.000	0.000
1960	-0.041	0.000	0.000	0.000
1961	-0.039	0.000	0.000	0.000
1962	-0.037	0.000	0.000	0.000
1963	-0.035	0.000	0.000	0.000
1964	-0.026	0.000	0.000	0.000
1965	-0.028	0.000	0.000	0.000
1966	-0.020	0.000	0.000	0.000
1967	-0.033	0.000	0.000	0.000
1968	-0.048	0.000	0.000	0.000
1969	-0.061	0.000	0.000	0.000
1970	-0.127	0.000	0.000	0.000
1971	-0.137	0.000	0.000	0.000
1972	-0.163	0.000	0.000	0.000
1973	-0.180	0.000	0.000	0.000
1974	-0.115	0.000	0.000	0.000
1975	-0.017	0.000	0.000	0.000
1976	-0.001	0.000	0.000	0.000
1977	-0.013	0.000	0.000	0.000
1978	-0.026	0.000	0.000	0.000
1979	-0.045	0.000	0.000	0.000
1980	-0.028	0.000	0.000	0.000
1981	0.000	0.000	0.000	0.000
1982	0.000	0.000	0.000	0.000
1983	0.000	0.000	0.000	0.000
1984	-0.004	0.000	0.000	0.000
1985	0.000	0.000	0.000	0.000
1986	-0.006	0.000	0.000	0.000
1987	0.000	0.000	0.000	0.000
1988	0.000	0.000	0.000	0.000
1989	0.000	0.000	0.000	0.000
1990	-0.019	0.000	0.000	0.000
1991	-0.008	0.000	0.000	0.000
1992	0.000	0.000	0.000	0.000
1993	-0.010	0.000	0.000	0.000
1994	-0.039	0.000	0.000	0.000

Table 2.4 **Technical Efficiency and Productivity Growth Estimates from Input Distance Function: The Canadian Pulp and Paper Industry, 1959-94**

year	Technical Efficiency	Malmquist Productivity Index Growth Rate	Malmquist Productivity Index (1959=1.00)
1959	1.000	..	1.000
1960	1.000	-2.00%	0.980
1961	1.000	-1.30%	0.968
1962	1.000	-1.50%	0.953
1963	1.000	-1.90%	0.935
1964	1.000	-1.90%	0.918
1965	1.000	-1.70%	0.902
1966	0.999	-1.80%	0.886
1967	0.991	-2.45%	0.865
1968	1.000	-0.43%	0.861
1969	1.000	-0.50%	0.857
1970	1.000	-0.20%	0.855
1971	1.000	-0.75%	0.848
1972	0.995	-2.05%	0.831
1973	1.000	-1.58%	0.818
1974	0.981	-3.65%	0.789
1975	1.000	1.75%	0.803
1976	0.968	-2.65%	0.782
1977	1.000	3.52%	0.810
1978	1.000	-0.17%	0.808
1979	0.988	-1.60%	0.796
1980	1.000	0.43%	0.799
1981	0.995	-1.15%	0.790
1982	0.979	-1.57%	0.778
1983	1.000	2.94%	0.801
1984	1.000	1.96%	0.817
1985	1.000	2.68%	0.839
1986	0.984	0.84%	0.846
1987	1.000	3.36%	0.875
1988	1.000	1.99%	0.892
1989	0.962	-1.56%	0.878
1990	1.000	6.46%	0.937
1991	1.000	3.19%	0.967
1992	1.000	3.97%	1.007
1993	1.000	3.52%	1.043
1994	1.000	2.63%	1.070
Averages:			
1959-1994	0.996	0.19%	0.878
1959-1969	0.999	-1.55%	0.920
1970-1979	0.993	-0.74%	0.814
1980-1989	0.992	0.99%	0.831
1990-1994	1.000	3.95%	1.005

Table 2.5 Single- and Total-Factor Productivity Growth Rates from the Tornqvist Index Formula: The Canadian Pulp And Paper Industry, 1959-94

Year	Energy	Capital	Virgin Fibre	All Materials	All Labour	TFP (All Inputs)
1959	..	..	..	..	..	..
1960	0.50%	3.54%	-1.81%	-0.14%	-1.50%	0.07%
1961	-0.91%	3.53%	-0.45%	-3.98%	4.44%	-0.34%
1962	0.47%	2.68%	-1.35%	-1.60%	1.00%	-0.15%
1963	-1.34%	0.23%	0.64%	-0.07%	2.21%	0.47%
1964	-1.49%	-2.87%	-0.27%	-2.17%	3.77%	-0.56%
1965	-0.82%	-8.11%	1.04%	1.23%	3.55%	0.71%
1966	2.40%	-8.20%	-0.65%	-0.33%	3.24%	0.06%
1967	-4.91%	-8.04%	-0.98%	-1.38%	0.53%	-2.04%
1968	-1.22%	7.08%	-2.04%	-0.74%	5.86%	2.14%
1969	3.72%	8.48%	0.62%	1.66%	7.12%	4.19%
1970	-4.01%	-8.98%	0.65%	-5.05%	-7.32%	-6.05%
1971	1.05%	-4.93%	1.74%	-0.91%	3.48%	-0.04%
1972	2.38%	6.10%	0.75%	-0.68%	6.19%	2.25%
1973	5.38%	10.09%	0.38%	0.05%	5.81%	2.72%
1974	-3.13%	5.92%	-1.71%	-3.07%	-2.81%	-2.88%
1975	-5.82%	-23.79%	-1.31%	-4.17%	-11.89%	-6.84%
1976	2.30%	18.72%	1.32%	3.48%	5.92%	4.47%
1977	5.88%	0.88%	3.07%	2.03%	4.95%	3.24%
1978	5.05%	9.76%	1.06%	-0.27%	5.56%	2.70%
1979	1.02%	2.41%	-2.57%	-4.12%	1.23%	-1.72%
1980	1.88%	-10.23%	-2.49%	-5.70%	-2.20%	-3.94%
1981	-1.18%	-21.59%	-2.60%	-2.03%	-5.36%	-4.32%
1982	-0.85%	-17.04%	0.42%	-1.77%	-4.78%	-3.82%
1983	12.02%	17.11%	3.33%	8.23%	16.00%	11.66%
1984	-0.60%	8.64%	1.29%	2.02%	4.72%	3.12%
1985	10.68%	3.91%	4.60%	3.03%	8.25%	5.51%
1986	-0.26%	-1.41%	-9.85%	-9.04%	0.30%	-4.55%
1987	6.50%	-7.19%	-0.68%	-0.05%	2.71%	0.49%
1988	0.21%	-9.50%	8.29%	3.36%	2.47%	1.00%
1989	-6.26%	-26.73%	-7.78%	-6.89%	-4.15%	-8.98%
1990	-11.00%	-12.08%	10.40%	8.36%	4.56%	1.84%
1991	3.31%	0.50%	-0.97%	2.91%	6.33%	3.21%
1992	7.68%	9.97%	-2.49%	2.54%	12.33%	6.79%
1993	5.14%	10.62%	6.60%	-1.88%	6.15%	2.98%
1994	-2.16%	11.09%	4.20%	-2.75%	3.86%	0.89%
Averages:						
1959-1969	-0.36%	-0.17%	-0.53%	-0.75%	3.02%	0.45%
1970-1979	1.01%	1.62%	0.34%	-1.27%	1.11%	-0.22%
1980-1989	2.21%	-6.40%	-0.55%	-0.88%	1.80%	-0.38%
1990-1994	0.60%	4.02%	3.55%	1.84%	6.65%	3.14%
1959-1994	0.90%	-0.84%	0.30%	-0.57%	2.64%	0.41%

NOTES

[1] Alternatively, $F^1(X)$ and $F^2(X)$ can be thought of as the production technologies of two firms operating in the same period, or at two different periods in time.

[2] The decomposition of TFP into its components can be carried out using input-oriented measures of efficiency and productivity. In fact, the empirical analysis in this study employs input-oriented rather than output-oriented measures. We start with output-oriented measures because these are more familiar to most readers. The decomposition of productivity change using input-oriented measures of technical change and efficiency is also discussed below.

[3] In terms of Figure 2-1, the production functions $F^1(X)$ and $F^2(X)$ would be constructed based on the most efficient observations in the frontier literature. Under the nonfrontier approach, these estimated functions would pass through clouds of observations for their respective periods.

[4] Other possible approaches include multi-lateral index number formulas like those introduced by Caves, Christensen and Diewert (1982b) which can be used to measure efficiency using cross-section or panel data. Such applications are relatively rare, however.

[5] For comprehensive surveys of the DEA technique, see Ali and Seiford (1993), for example. Coelli, Rao and Battese (1998) and Lovell (1993) provide good introductions to the DEA literature.

[6] See Shephard (1970) and Fare and Primont (1995) for a detailed treatment of distance functions and their duality relationships.

[7] $D(u,x,t)=0$ if $(u,x) \notin \Delta = \{(u,x) | u \geq 0, x \geq 0, \exists \lambda > 0 \text{ such that } (u,\lambda x) \in Y(t)\}$. And $D(0,x,t) = +\infty$.

[8] The input distance function is decreasing in *u* only in the absence of undesirable outputs.

[9] Free disposability of inputs simply means there are no holes in the input requirement set L(u), i.e. $x \in L(u) \Rightarrow x/\delta \in L(u) \; \forall \; \delta \in (0,1]$.

[10] Simply by using Euler's theorem. This is also intuitive, from the very definition of input distance functions.

[11] The firms *k* and *l* could be the same firm at two different points in time, or two firms at the same or different points in time.

[12] These are an Atlantic Packaging Products mill in Whitby, Ontario, an Alberta Newsprint mill in Whitecourt, Alberta, and a Howe Sound Pulp and Paper mill in Port Mellon, British Colombia. They have annual production capacities of 150, 180, and 195 thousand tonnes of newsprint, respectively.

[13] The α_n's are the first order coefficients for the inputs such that the subscript numbers 1,2,...,7 represent, respectively, energy, wood residue, pulpwood, non-wood materials, production labour input, administration workers, and capital. The β_m's are the first order coefficients for the outputs where the subscripts 1,2,...,4 represent net output of wood pulp, newsprint, paper other than newsprint, and paperboards and building boards, respectively.

[14] For concavity all eigenvalues should be non-positive.

[15] For quasi-concavity $BH2, BH4 \geq 0 \geq BH1, BH3$.

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CHAPTER 3 An Input Distance Function Approach to Environmentally Sensitive Productivity and Efficiency Analysis

3.1 Introduction

Conventional measures of productivity and efficiency such as those employed in the second chapter of this thesis account for saleable or marketed outputs and inputs while ignoring changes in undesirable outputs that are jointly produced with marketed goods. Therefore, the costs of pollution abatement are included as inputs while the social benefits of improved environmental quality are generally ignored. In the case of the Canadian pulp and paper industry, for example, the share in total capital expenditure of capital spending for pollution abatement increased from 5.48 percent in the period from 1960 to 1971 to 25 percent in the early 1990s. This increased expenditure has brought with it a large reduction in the output rates of traditional pollutants such as BOD and TSS. These changes in pollutant outputs were not taken into account in the analysis in Chapter 2. Such asymmetric treatment of marketed "goods" and "bads" leads to distortions in our assessment of changes in social well being and distorted pictures of relative economic performance (Fare *et al* 1993; Repetto *et al* 1996, 1997). This also leads to misguided policy recommendations.

This study uses input distance functions to provide a framework for a more complete representation of production technology, from which environmentally sensitive productivity and efficiency measures can be generated. Both desirable (marketable) outputs and undesirable (BOD and TSS) outputs are incorporated into the analysis. The approach has the additional advantage that it allows us to estimate producer shadow prices of pollutant outputs. The producer abatement cost information thus generated can be useful for evaluating and guiding environmental policy and for further economic analysis.

Some attempts have been made in the literature to incorporate pollutant outputs in efficiency and productivity analysis(e.g. Pittman 1983; Fare *et al* 1993; Repetto *et al* 1996; and Coggins and Swinton 1995). Pittman (1983) provided the earliest attempt at incorporating undesirable outputs in efficiency measurement. He used shadow prices calculated from abatement costs in his computation of enhanced Caves-Christensen-Diewert (1982) multilateral productivity indexes to compare the productive efficiencies of a sample of 30 pulp and paper mills operating in Wisconsin in 1976. More recently, a study by Repetto *et al* (1996) used adjusted non-market valuation estimates of the marginal pollution damage values to compute adjusted productivity indexes for three US industries, including the pulp and paper industry.

These index number approaches depend on external damage value estimates (as in the Repetto *et al* (1996) study) or on the estimation of pollutant shadow prices from abatement expenditure by producers (as in the study by Pittman). Estimating abatement costs is likely to become less and less practical because it is increasingly difficult to distinguish between "productive" and pollution abatement expenditures on capital or other inputs. Pollution damage estimate values are difficult to get. Moreover, the accuracy and transferability across regions and time periods of these non-market valuations of pollution damages are similarly open to question.

The use of distance functions incorporating both desirable and pollutant outputs can help overcome the problems associated with the index number approaches discussed above. Fare *et al* (1993) and Coggins and Swinton (1995) use output distance functions for this purpose. Fare *et al* (1993) used Pittman's data to estimate an output distance function from which they calculated efficiency measures and producer specific shadow prices for pollutant outputs. Coggins and Swinton (1995) use the method to estimate sulphur dioxide shadow prices for 14 coal-burning electric plants in Wisconsin.

3.2 Input Distance Function with Pollutant Outputs

This study uses input distance functions to analyze productivity trends in the Canadian pulp and paper industry in environmentally sensitive ways. Both input and output distance functions are capable of handling multi-output technologies. Nonetheless, input distance function were chosen for this analysis because the efficiency interpretation of the input distance function values remains unambiguous even when pollutant outputs are incorporated into the analysis.

The input distance function was formally defined in equation (2.1) as the function that indicates, for a given or observed combination of inputs and outputs, the maximal proportion by which the input vector should be deflated to bring it to the frontier of the input requirement set. The output vector or u is now interpreted more broadly to include a subvector v of desirable outputs and a subvector w of pollutant or undesirable outputs. The properties of the input distance function with respect to inputs and desirable outputs as well as the definitions of and formulas for efficiency, technical change, Malmquist indexes and returns to scale measures also remain the same as discussed in Chapter 2.[1]

We will, however, distinguish between the monotonicity properties of the input distance function with respect to desirable and undesirable outputs. Since the function measures the maximum radial contraction in the input vector that is consistent with the production of the observed output vector, it was indicated in Chapter 2 that the function should be non-decreasing in inputs and non-increasing in desirable outputs. In this chapter we will impose the additional requirement that the function be non-decreasing in pollutant outputs. This is because a reduction in pollutant outputs requires the use of additional inputs for abatement, other outputs remaining the same. This additional requirement is incorporated into the estimation of the parameters of the distance function as described later.

3.3 Pollutant Shadow Price Derivation

Not only does the distance function approach not require external estimates of pollution damage values, but it can also be used to derive producer shadow prices for pollutants that can be useful for other analyses or to guide environmental policy. Moreover, the shadow prices are derived under the mild[2] assumption of producer cost minimization behavior.

The cost function is the solution to the following minimization problem:

$$C(u,p,t) = Min_x \left\{ p.x \middle| D(u,x,t) \geq 1,\ x \in R^{N}_{=} \right\} \qquad (3.1)$$

where $p \in R^{N}{}_{+}$ is the input price vector. Equation (3.1) is the duality relationship between the cost and input distance functions due to Shephard (Shephard 1953, 1970; Fare and Primont 1995). Upon a straightforward application of the envelope theorem on the first order conditions, the above cost minimization problem yields the following output shadow price formulas:

$$\begin{aligned} \nabla_u C(u,p,t) \quad &= -\Lambda(u,p,t).\nabla_u D(u,x,t) \\ &= -C(u,p,t).\nabla_u D(u,x,t) \end{aligned} \qquad (3.2a)$$

The first equation follows directly from the first order conditions for the solutions to (3.1). The second equation obtains because the Lagrangian multiplier (Λ) is equal to the value of the optimized cost function. The shadow price of a given output is the increase in costs that the production of an additional unit of the output entails. The shadow prices for pollutant outputs will be non-positive, as the input distance function is non-decreasing in pollutant outputs.

If we do not know about the accuracy of the cost of production estimates, we can use the following alternative formula derived from (3.2a) to calculate the ratio of the shadow price of output *i* to that of output *j*:

$$\frac{r_i^*}{r_j^*} = \frac{\partial D(u,x,t)}{\partial u_i} \bigg/ \frac{\partial D(u,x,t)}{\partial u_j} \qquad (3.2b)$$

Thus the ratio of the shadow prices is equal to the trade off between the two inputs – how much of units of output *j* the producer would be willing to forego for the right to emit one more unit of pollutant output *i*. And if we assume that the market price of u_j equals its shadow price, we can calculate the shadow price (r^*_i) of pollutant output u_i as follows:

$$r_i^* = r_j^* \left(\frac{\partial D(u,x,t)}{\partial u_i} \bigg/ \frac{\partial D(u,x,t)}{\partial u_j} \right) \qquad (3.2c)$$

This formula is used in this study to calculate shadow prices for the two water pollutants, BOD and TSS, included in the estimation of the input distance function.

3.4 Functional Form and Estimation of Input Distance Function

As in Chapter 2, the flexible translog functional form (Christensen, Jorgenson and Lau 1973) was chosen for the input distance function:

$$\begin{aligned}\ln\ D(u,x,t) &= \alpha_o + \sum_{n=1}^{N} \alpha_n . \ln x_n + \sum_{m=1}^{M} \beta_m . \ln u_m \\ &+ (0.5) \sum_{n=1}^{N} \sum_{n'=1}^{N} \alpha_{nn'} . \ln x_n . \ln x_{n'} \\ &+ (0.5) \sum_{m=1}^{M} \sum_{m'=1}^{M} \beta_{mm'} . \ln u_m . \ln u_{m'} \qquad (3.3) \\ &+ (0.5) \sum_{n=1}^{N} \sum_{m=1}^{M} \gamma_{nm} . \ln x_n . \ln u_m \\ &+ \alpha_t . t + (0.5) . \alpha_{tt} . t^2 \\ &+ \sum_{n=1}^{N} \alpha_{nt} . t . \ln x_n + \sum_{m=1}^{M} \beta_{mt} . t . \ln u_m \end{aligned}$$

where: n indexes the vector of inputs such that the subscript numbers 1,2,...,7 represent, respectively, energy, wood residue, pulpwood, non-wood materials, production labour input, administration workers, and capital; m indexes the output vector of the firm such that the subscripts 1,2,3, and 4 represent marketed outputs of wood pulp, newsprint, paper other than newsprint, and paperboards and building boards, respectively, while 5 and 6 represent pollutant outputs of biological oxygen demand (BOD) and total suspended solids (TSS), respectively; and t denotes time trend.

The estimation problem was formulated as a linear programming problem similar to that used in Chapter 2 but with the additional constraint that the input distance function be non-decreasing in pollutant outputs. The objective in the problem is to choose the set of parameter estimates that minimizes the sum of deviations of the values of the distance function from unity. That is, the estimation takes the following optimization problem form:

$$Minimize_{(\alpha,\beta,\gamma)} \sum_{t=1}^{36} ln\, D(u,x,t) \qquad (LP2)$$

Subject to the following constraints:

$$ln\, D(u,x,t) \geq 0, \quad t = 1,\ldots, 36 \qquad (C1)$$

$$\frac{\partial\, ln\, D(u,x,t)}{\partial x_n} \geq 0, \quad t = 1,\ldots, 36, \; n = 1,\ldots, 7 \qquad (C2)$$

$$\frac{\partial\, ln\, D(u,x,t)}{\partial u_m} \leq 0, \quad t = 1,\ldots, 36, \; m = 1,\ldots, 4 \qquad (C3)$$

$$\frac{\partial\, ln\, D(u,x,t)}{\partial u_m} \geq 0, \quad t = 1,\ldots, 36, \; m = 5,6 \qquad (C4)$$

$$\sum_{n=1}^{7} \alpha_n = 1 \qquad (C5a)$$

$$\sum_{n=1}^{7} \alpha_{nn'} = 1, \quad n' = 1,\ldots, 7 \qquad (C5b)$$

$$\sum_{n=1}^{7} \gamma_{nm} = 0, \quad m = 1,\ldots, 6 \qquad (C5c)$$

$$\sum_{n=1}^{7} \alpha_{nt} = 0, \qquad (C5d)$$

$$\alpha_{nn'} = \alpha_{n'n}, \quad n, n' = 1,\ldots, 7 \qquad (C6a)$$

$$\beta_{mm'} = \beta_{m'm}, \quad m, m' = 1,\ldots, 6 \qquad (C6b)$$

The first set of constraints (C1) ensures that the estimated function identifies the observation as one that is within the technology frontier (that it is feasible and thus its distance function value should be unity or higher). The second set of constraints (C2) imposes the monotonicity condition that the distance function be non-decreasing in inputs. The third set of constraints (C3) requires that the function be a non-increasing function of the four marketable or disposable outputs, while the constraints in (C4) ensure that the estimated input distance function is non-decreasing in the two pollutant outputs. The remaining set of constraints ensure the linear homogeneity of the input distance function with respect to inputs (C5) and the symmetry conditions for the translog (C6).

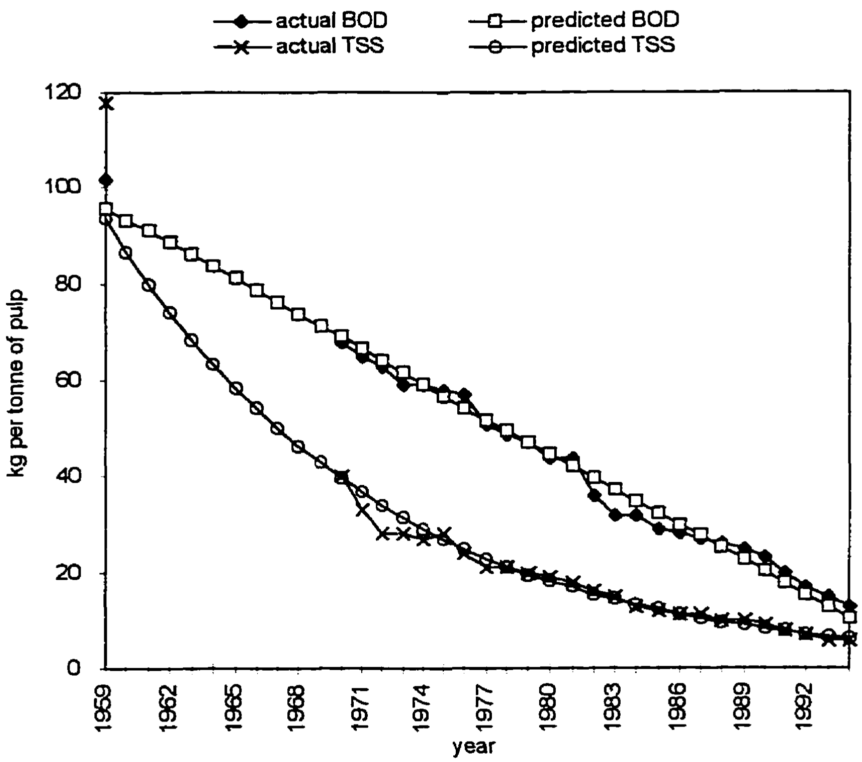
In other words, the parameter estimation for the input distance function with pollutant outputs is carried out by minimizing the sum of deviations from unity subject to 555 constraints. These are 36 feasibility constraints; 468 monotonicity constraints relating to inputs (252), desirable outputs (144) and pollutant outputs (72); 15 linear homogeneity conditions, and 36 translog symmetry restrictions. This large linear programming problem was written in GAMS solved to compute the parameter estimates. The estimation procedures employed here are very similar to those in Fare et al (1993) and Coggins and Swinton (1995) but with monotonicity conditions relating to inputs imposed in addition to those relating to outputs.

3.4 Data

Industry aggregate time series data set for the period from 1959 to 1994 is used. Each of these 36 observations include data on four desirable outputs, two undesirable outputs and seven inputs were identified in this study. The four desirable output categories include net pulp output, newsprint production, paper other than newsprint[3], and paperboards and building boards. The undesirable outputs are biological oxygen demand (BOD) and total suspended solids (TSS) in water effluent from the industry. The seven input categories are: energy, wood residue, pulpwood, non-wood materials, production labour hours, number of administration workers, and capital.

The sources of quantity and price data for the seven inputs and the four marketable outputs of the industry are described in detail in the last section of the introductory chapter. Pollution data for the industry were obtained by request from the Canadian Pulp and Paper Association (CPPA). Biological oxygen demand (BOD) and total suspended solids (TSS) rates were available only for

Figure 3.1
Actual and Regression Equation Predicted BOD and TSS Rates:
Canadian Pulp and Paper Industry, 1959-1994



1959 and for 1970 to 1994. The rates for 1960 to 1969 were interpolated from regressions of pollutant rates on time trend. BOD and TSS pollution output per wood pulp production rates exhibit very clear and consistent trends time trends.

In the period from 1959 to 1994, BOD rates declined from 102 kg per tonne to 13 kg per tonne of wood pulp production. The decline followed a linear trend. The following results were obtained for the regression of BOD rates on time trend (t):

$$BOD\ rate = 98.1524 - 2.4342\ (time\ trend)$$

The R-square for this regression was 98.51 percent and the standard errors for the intercept and the slope were, respectively, 2.5952 and 0.0610.

TSS rates declined from 118 in 1959 to only 6 kg per tonne of pulp in 1994. These rate changes, however, followed a log-linear trend over time rather than a linear one. The estimated regression equation is,

$$\log\ (TSS\ rate) = 4.6164 - 0.0781\ (time\ trend)$$

The R-square value for this regression is 98.45 percent while the intercept and slope standard errors were 0.0850 and 0.0020, respectively. The actual and predicted BOD and TSS rates are plotted in in Figure 3.1.

3.5 Results and Discussion

As in the case of the analysis without pollutant outputs, the estimated input distance function was found to be concave in inputs and quasi-concave with respect to outputs for all the years. The function curvature test results are reported in Tables 3.2 and 3.3. The parameter estimates from the analysis incorporating pollutant outputs are shown in Table 3.1.

Also, the efficiency and returns to scale estimates from the input distance function with pollutant outputs are similar to those obtained from the function estimated without pollutant outputs. An average returns to scale estimate of 1.27 was obtained. The average level of productive efficiency obtained in this chapter was similarly high, at 99.6 percent. More or less the same observations are identified as periods of less than 100 percent technical efficiency in both studies.

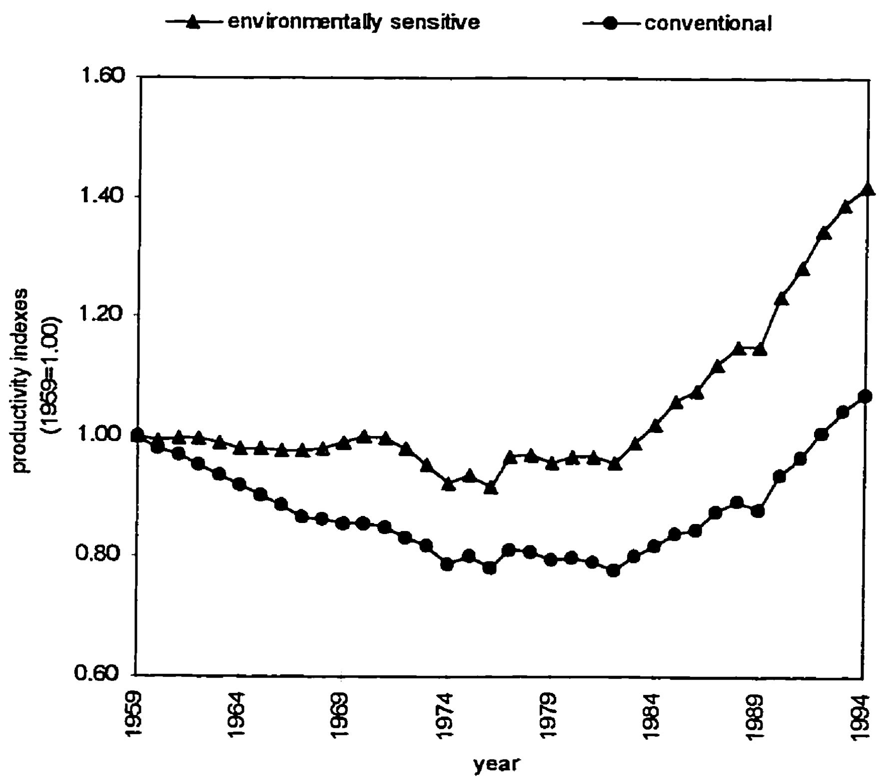
Productivity growth estimates, however, change dramatically when pollutant outputs are incorporated into the analysis. The average annual growth rate of the Malmquist index[4] obtained from the input distance function that includes undesirable outputs is 1.00 percent. This estimate is substantially higher than the rate of 0.19 percent calculated from the input distance function involving no pollutant outputs.

The results also show that most of the productivity growth in the Canadian pulp and paper industry occurred in the period after the 1981-82 recession. Productivity growth was fastest (at 4.19 percent per year) in the 1990-93 period than in earlier periods. Mean productivity growth estimates of –0.12, -0.32, and 1.84 were obtained for the 1959-1969, 1970-79, and 1980-89 periods, respectively. The environmentally sensitive measures of productivity improvement are higher than the conventional ones obtained in Chapter 2 for the same periods. See Table 3.4 for the complete efficiency and productivity growth estimates. As indicated in the discussion with regards to the results from the conventional measures in Chapter 2, the reasons for the very rapid productivity growth in the early 1990s include the change in the mill composition of the industry which increased the proportion of mills with modern technology.

While the conventional estimates from Chapter 2 indicate that productivity growth was higher in the 1970s than in the 1960s, the results obtained when pollutants are included indicate the opposite. The growth rate declines from -0.12 in the 1960s to -0.32 percent in the 1970s. This is partly due to the economic contractions resulting from the two oil crises of the 1970s and a generally lower capacity utilization rate in the 1970s. There was also an increase in pollution abatement expenditure in the 1970s following the introduction of new regulations aimed at reducing water pollution. As a result the share of pollution abatement capital expenditure jumped from only 5.4 percent of total capital expenditure for the period from 1960 to 1971 to 12.2 percent for the period from 1972 to 1979[5]. But the reduction in pollutant outputs rates was faster in the 1960s, especially in the case of TSS, the production of which declined by 66 percent from 118 kg/ tonne of pulp in 1959 to 40 kg/tonne of pulp in 1970. The production of BOD also declined by 33 percent from 102 kg/tonne of pulp to 68 kg/tonne of pulp over the same period. The reduction rates in the 1970 were lower (53 percent) for TSS, although they were slightly higher (35 percent) for BOD. In other words, a much faster reduction in pollutant output was achieved in the 1960s using mainly lower cost primary treatment facilities that were effective in reducing TSS output and, to a lower degree, BOD output. Thus, when pollutant outputs are incorporated into the productivity measures, the reduced effectiveness of resources used in pollution abatement contributes to the reduction in the rate of productivity growth. However, the gap between environmentally sensitive and conventional estimates of productivity is highest for the 1960s, when pollution reduction was most rapid.

The productivity indexes from the input distance function with and without undesirable outputs are plotted in the chart in Figure 3.2. Productivity measured in environmentally sensitive ways is higher than the conventional measure of productivity throughout the period. According to the conventional measure, the productivity of the Canadian pulp and paper industry increased only by 7 per cent over the entire 36 year period from 1959 to 1994. By comparison, the results from the analysis with pollutant outputs indicate that the industry was 41.8 per cent more productive in 1994 than it was in 1959.

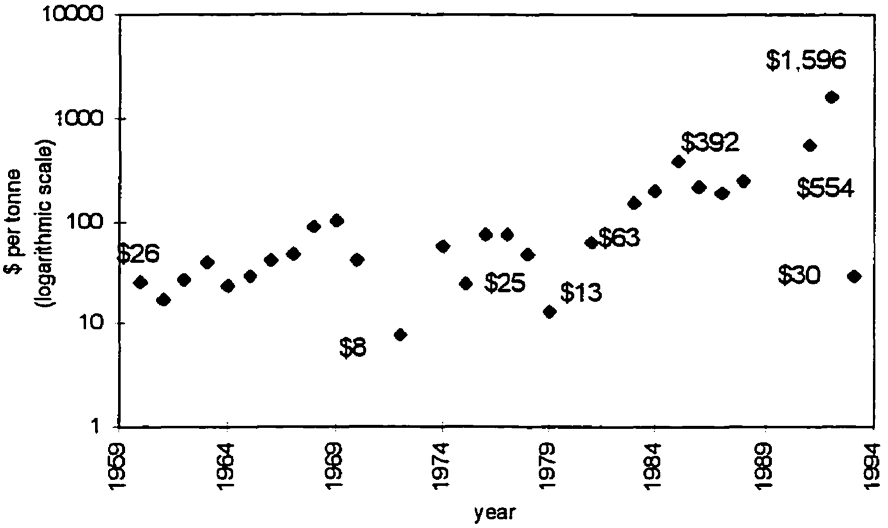
Figure 3.2
Malmquist Productivity Indexes for the Canadian Pulp and Paper Industry, 1959-1994: Results from Input Distance Functions



3.5.1 Abatement Cost or Shadow Price Estimates for Pollutants

Pollutant shadow prices were calculated using equation (3.2c). The market price of paperboards was assumed to be equal to its shadow price. Then the pollutant shadow prices were determined by multiplying the price of paperboards and the ratio of the derivative values of the input distance function with respect to the pollutant and to paperboards. The ratio of these derivatives reflects the trade-off between the pollutant and paperboard, from the perspective of the producer. The calculated shadow prices measure the cost of pollution abatement to the producer (and also to society). These prices can be compared to the benefits of pollution abatement (or damages from environmental pollution) to assess the optimality of current environmental regulations. The estimated shadow prices are plotted in Figures 3.3 and 3.4.

Figure 3.3
Biological Oxygen Demand (BOD) Abatement Cost (Shadow Price) Estimates Derived from Input Distance Function: Canadian Pulp and Paper Industry, 1959-1994

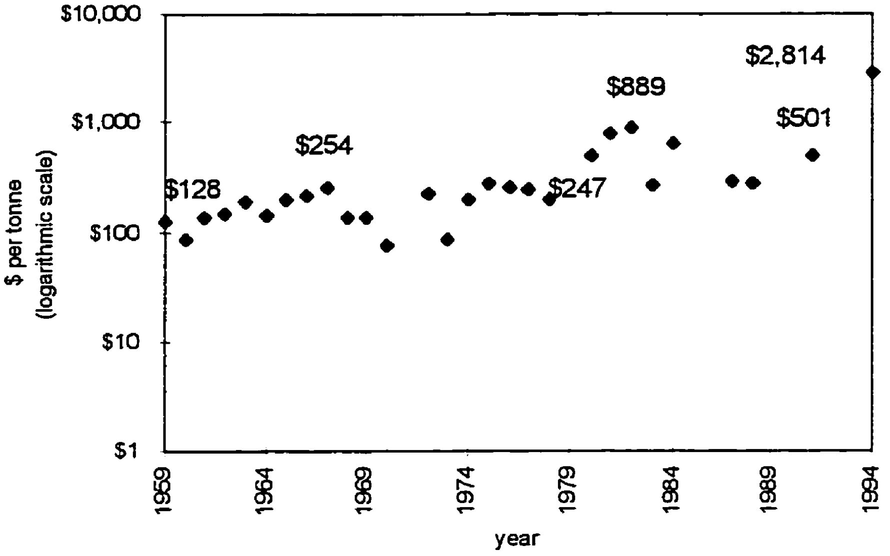


One minor problem, an artefact of the LP nature of the estimation of the distance function parameters, was encountered in the implementation of the above procedure. For some of the years, the monotonicity constraints relating either to the pollutant or paperboards were binding. This results in a derivative ratio that has a value of zero numerator or zero denominator. The zero estimates of shadow prices were left and reported as such.[6] But for the few (three) years[7] for which the pollutant-paperboard had a zero denominator, the pollutant shadow price was calculated using equation (3.2a) instead of (3.2c). The meaning of the estimate, however, remains the same – the shadow price thus calculated indicates the abatement cost that the producer would incur if she/he were to reduce pollutant output by one unit, at the margin.

The trends in the computed pollutant shadow price estimates indicate the effects of the diminishing returns to pollution abatement. The calculated shadow prices of biological oxygen demand (BOD) were generally less than $100 for the first two decades covered in the study. The average shadow prices for the 1960s and the 1970s were very close. The prices for the 1980's and the '90s are, however, much higher. The average BOD shadow price increases from $34 for the 1970s to $147 per metric tonne for the 1980's and to $436 per metric tonne for the period from 1990 to 1994. The average value of the BOD shadow prices for the sample period 1959 to 1994 is $123 per metric tonne.

Shadow prices for total suspended solids were generally found to be higher than shadow price estimates for biological oxygen demand. For the period from 1959 to 1994, the average of the TSS shadow prices was calculated to be $286 per metric tonne. Like the BOD prices, the TSS prices show increasing trends over time. TSS shadow price estimates ranged between $100 and $300 during the 1960s and 1970s with average values of $161 and $157 per metric tonne, respectively. Average prices of $365 and $663 per metric tonne of TSS were calculated for the 1980 to 1989 and 1990 to 1994 periods, respectively.

Figure 3.4
Total Suspended Solids (TSS) Abatement Cost (Shadow Price) Estimates Derived from Input Distance Function: The Canadian Pulp and Paper Industry, 1959-1994



3.6 Summary and Conclusion

This study attempted to analyze productivity trends in the Canadian pulp and paper industry in a way that is sensitive to the environmental effects of the industry's production activity. This was done by estimating a parametric input distance function frontier that incorporates both desirable and undesirable outputs. The parameters of the function were estimated using mathematical programming. Data covering the period from 1959 to 1994 are used. Four desirable outputs, two water pollutant outputs (BOD and TSS) and seven inputs were identified for the estimation of the input distance function.

The degree of productive or technical efficiency was found to be high during most of the periods. This is not surprising, given the nature of the data (a single time series) and the objective function (minimizing the sum of deviations from the frontier) of the parameter estimation procedure. If instead, panel data were used, efficiency level estimates would then be computed by comparing different observations from the same period as well as different periods. The greater the number of observations that a given observation is compared to, the lower the efficiency estimate for that observation is likely to be. But interestingly, many of the periods identified as inefficient in our estimation coincide with oil crises and macroeconomic recession periods. Similar technical efficiency results were also obtained in Chapter 2. As in Chapter 2, the results also indicate that production in the Canadian pulp and paper industry is characterized by modest increasing returns to scale.

The technical change estimates indicate that productivity measures that ignore pollutant outputs substantially underestimate the performance of the industry. Our environmentally sensitive approach indicates that the total factor productivity of the industry has been growing at the rate of 1.00 percent per year over the period from 1959 to 1994. This is higher than most of the productivity growth estimates obtained for the industry, regardless of whether those estimates include output scale effects in addition to technical change and efficiency improvement. This estimate is also considerably higher than the estimate of 0.19 percent per year that we obtained from the input distance function estimated without pollutant outputs. The main conclusion of this study is that productivity improvement, from the social viewpoint, has been stronger than conventional measures would suggest. Our shadow price estimates, however, indicate that the cost to producers of pollution control has been rising as the rates of pollutant outputs of biological oxygen demand (BOD) and total suspended solids (TSS) declined.

Table 3.1 **Parameter Estimates for Input Distance Function with Pollutant Outputs: Canadian Pulp and Paper Industry, 1959-94**[8]

$\alpha1$	-5.348	$\alpha26$	0.230	$\beta23$	0.162	$\gamma25$	-0.103	$\gamma65$	0.084
$\alpha2$	2.914	$\alpha27$	-0.194	$\beta24$	-2.123	$\gamma26$	-0.293	$\gamma66$	-0.072
$\alpha3$	-2.621	$\alpha33$	-0.091	$\beta25$	0.226	$\gamma31$	-0.331	$\gamma71$	0.033
$\alpha4$	6.749	$\alpha34$	-0.145	$\beta26$	0.729	$\gamma32$	0.590	$\gamma72$	-0.526
$\alpha5$	-1.891	$\alpha35$	-1.035	$\beta33$	-1.093	$\gamma33$	-0.762	$\gamma73$	-0.004
$\alpha6$	-0.697	$\alpha36$	-0.521	$\beta34$	2.025	$\gamma34$	-1.343	$\gamma74$	0.348
$\alpha7$	1.894	$\alpha37$	-0.024	$\beta35$	-0.266	$\gamma35$	0.338	$\gamma75$	-0.012
$\beta1$	-3.790	$\alpha44$	-0.223	$\beta36$	-0.708	$\gamma36$	0.173	$\gamma76$	0.064
$\beta2$	-7.817	$\alpha45$	-0.744	$\beta44$	-1.298	$\gamma41$	-0.611	αT	-0.913
$\beta3$	4.222	$\alpha46$	-0.146	$\beta45$	0.191	$\gamma42$	-0.939	αTT	0.015
$\beta4$	7.373	$\alpha47$	0.434	$\beta46$	0.508	$\gamma43$	0.556	$\alpha1T$	0.056
$\beta5$	-2.675	$\alpha55$	1.966	$\beta55$	-0.086	$\gamma44$	0.289	$\alpha2T$	-0.045
$\beta6$	-1.178	$\alpha56$	0.353	$\beta56$	-0.087	$\gamma45$	-0.474	$\alpha3T$	0.065
$\alpha11$	-0.201	$\alpha57$	0.112	$\beta66$	-0.236	$\gamma46$	0.142	$\alpha4T$	-0.107
$\alpha12$	-0.449	$\alpha66$	0.022	$\gamma11$	-0.472	$\gamma51$	1.405	$\alpha5T$	0.045
$\alpha13$	1.558	$\alpha67$	-0.117	$\gamma12$	2.365	$\gamma52$	-1.810	$\alpha6T$	-0.017
$\alpha14$	-0.424	$\alpha77$	-0.080	$\gamma13$	-0.220	$\gamma53$	-0.463	$\alpha7T$	0.002
$\alpha15$	-0.533	$\beta11$	0.104	$\gamma14$	-0.045	$\gamma54$	0.186	$\beta1T$	0.064
$\alpha16$	0.180	$\beta12$	0.107	$\gamma15$	-0.104	$\gamma55$	0.270	$\beta2T$	0.098
$\alpha17$	-0.132	$\beta13$	-0.737	$\gamma16$	-0.091	$\gamma56$	0.077	$\beta3T$	-0.096
$\alpha22$	-0.972	$\beta14$	0.119	$\gamma21$	0.139	$\gamma61$	-0.162	$\beta4T$	-0.110
$\alpha23$	0.257	$\beta15$	0.205	$\gamma22$	0.337	$\gamma62$	-0.017	$\beta5T$	0.019
$\alpha24$	1.248	$\beta16$	-0.102	$\gamma23$	0.476	$\gamma63$	0.409	$\beta6T$	0.015
$\alpha25$	-0.120	$\beta22$	0.716	$\gamma24$	0.926	$\gamma64$	-0.360	$\alpha0$	29.833

Table 3.2 Test Results for Concavity in Inputs of the Estimated Input Distance Function: Analysis Incorporating Pollutant Outputs[9]

year	EIGENVALUE 1	EIGENVALUE 2	EIGENVALUE 3	EIGENVALUE 4	EIGENVALUE 5	EIGENVALUE 6	EIGENVALUE 7
1959	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1960	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1961	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1962	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1963	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1964	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1965	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1966	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1967	-0.001	0.000	0.000	0.000	0.000	0.000	0.000
1968	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1969	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1970	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1971	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1972	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1973	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1974	-0.001	0.000	0.000	0.000	0.000	0.000	0.000
1975	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1976	-0.002	0.000	0.000	0.000	0.000	0.000	0.000
1977	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1978	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1979	-0.001	0.000	0.000	0.000	0.000	0.000	0.000
1980	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1981	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1982	-0.001	0.000	0.000	0.000	0.000	0.000	0.000
1983	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1984	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1985	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1986	-0.001	0.000	0.000	0.000	0.000	0.000	0.000
1987	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1988	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1989	-0.001	0.000	0.000	0.000	0.000	0.000	0.000
1990	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1991	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1992	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1993	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1994	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table 3.3 Determinantal Test of Quasi-Concavity in Outputs of Estimated Input Distance Function: Analysis Incorporating Pollutant Outputs[10]

	Determinants of the principal minors of the bordered Hessian:					
year	BH1	BH2	BH3	BH4	BH5	BH6
1959	-0.215	0.000	0.000	0.000	0.000	0.000
1960	-0.097	0.000	0.000	0.000	0.000	0.000
1961	-0.065	0.000	0.000	0.000	0.000	0.000
1962	-0.057	0.000	0.000	0.000	0.000	0.000
1963	-0.045	0.000	0.000	0.000	0.000	0.000
1964	-0.037	0.000	0.000	0.000	0.000	0.000
1965	-0.037	0.000	0.000	0.000	0.000	0.000
1966	-0.034	0.000	0.000	0.000	0.000	0.000
1967	-0.037	0.000	0.000	0.000	0.000	0.000
1968	-0.046	0.000	0.000	0.000	0.000	0.000
1969	-0.051	0.000	0.000	0.000	0.000	0.000
1970	-0.152	0.000	0.000	0.000	0.000	0.000
1971	-0.142	0.000	0.000	0.000	0.000	0.000
1972	-0.148	0.000	0.000	0.000	0.000	0.000
1973	-0.169	0.000	0.000	0.000	0.000	0.000
1974	-0.102	0.000	0.000	0.000	0.000	0.000
1975	-0.024	0.000	0.000	0.000	0.000	0.000
1976	0.000	0.000	0.000	0.000	0.000	0.000
1977	-0.006	0.000	0.000	0.000	0.000	0.000
1978	-0.012	0.000	0.000	0.000	0.000	0.000
1979	-0.022	0.000	0.000	0.000	0.000	0.000
1980	-0.018	0.000	0.000	0.000	0.000	0.000
1981	0.000	0.000	0.000	0.000	0.000	0.000
1982	0.000	0.000	0.000	0.000	0.000	0.000
1983	0.000	0.000	0.000	0.000	0.000	0.000
1984	0.000	0.000	0.000	0.000	0.000	0.000
1985	0.000	0.000	0.000	0.000	0.000	0.000
1986	-0.002	0.000	0.000	0.000	0.000	0.000
1987	0.000	0.000	0.000	0.000	0.000	0.000
1988	0.000	0.000	0.000	0.000	0.000	0.000
1989	0.000	0.000	0.000	0.000	0.000	0.000
1990	-0.006	0.000	0.000	0.000	0.000	0.000
1991	-0.002	0.000	0.000	0.000	0.000	0.000
1992	0.000	0.000	0.000	0.000	0.000	0.000
1993	-0.004	0.000	0.000	0.000	0.000	0.000
1994	-0.022	0.000	0.000	0.000	0.000	0.000

Table 3.4 Shadow Prices, Technical Efficiency and Productivity Growth Estimates from Input Distance Function Incorporating Pollutant Outputs: Canadian Pulp and Paper Industry, 1959-1994

year	Technical Efficiency	Malmquist Productivity Index Growth Rate	Malmquist Productivity Index (1959=1.00)	BOD Shadow Prices ($/MT)	TSS Shadow Prices ($/MT)
1959	1.000	..	1.000	$0	$128
1960	1.000	-0.83%	0.992	$26	$85
1961	1.000	0.36%	0.995	$17	$137
1962	1.000	0.03%	0.996	$27	$147
1963	1.000	-0.80%	0.988	$40	$189
1964	1.000	-0.70%	0.981	$24	$145
1965	1.000	-0.15%	0.979	$29	$197
1966	0.998	-0.20%	0.977	$42	$218
1967	0.997	-0.20%	0.976	$48	$254
1968	1.000	0.32%	0.979	$89	$134
1969	1.000	1.00%	0.988	$101	$135
1970	1.000	1.10%	0.999	$42	$76
1971	1.000	-0.32%	0.996	$0	$0
1972	1.000	-1.80%	0.978	$8	$225
1973	1.000	-2.75%	0.952	$0	$88
1974	0.989	-3.15%	0.922	$58	$197
1975	1.000	1.51%	0.936	$25	$282
1976	0.962	-2.16%	0.916	$76	$260
1977	1.000	5.14%	0.965	$76	$247
1978	1.000	0.50%	0.969	$48	$199
1979	0.985	-1.29%	0.957	$13	$0
1980	1.000	0.98%	0.966	$0	$493
1981	1.000	-0.07%	0.966	$63	$802
1982	0.983	-0.90%	0.957	$0	$889
1983	1.000	3.33%	0.990	$151	$261
1984	1.000	3.00%	1.020	$203	$630
1985	1.000	3.80%	1.059	$392	$0
1986	0.985	1.67%	1.077	$217	$0
1987	1.000	3.85%	1.119	$193	$294
1988	1.000	2.87%	1.152	$247	$281
1989	0.965	-0.14%	1.150	$0	$0
1990	1.000	7.18%	1.236	$0	$0
1991	1.000	3.95%	1.285	$554	$501
1992	1.000	4.41%	1.343	$1,596	$0
1993	1.000	3.36%	1.389	$30	$0
1994	1.000	2.06%	1.418	$0	$2,814
Averages:					
1959-1994	0.996	1.00%	1.044	$123	$286
1959-1969	1.000	-0.12%	0.986	$40	$161
1970-1979	0.994	-0.32%	0.959	$34	$157
1980-1989	0.993	1.84%	1.046	$147	$365
1990-1994	1.000	4.19%	1.334	$436	$663

NOTES

[1] The input distance function has a finite value for a non-zero output vector; it is an increasing, concave and linearly homogeneous in the input vector; and it is upper semi-continuous and quasi-concave function of the output vector. An input distance function provides a complete characterization of the production technology if inputs are freely disposable.

[2] That is by comparison to the assumption of profit maximization.

[3] This category includes the following: printing and writing papers, wrapping paper, sanitary and specialty papers, and building papers.

[4] The Malmquist index growth rates are computed by summing technical change and technical efficiency growth rates using equation (2.9).

[5] These figures are based on pollution abatement capital expenditure data obtained by request from the Canadian Pulp and Paper Association.

[6] This occurred in 1959, 1971, 1973, 1980, 1982, 1989, 1990, and 1994 for BOD. For TSS, zero derivative values were obtained 1971, 1979, 1985-6, 1989, 1990, 1992-3.

[7] The derivative of the input distance function with respect to paperboards was zero only for 1967, 1968, and 1971.

[8] The α_n's are the first order coefficients for the inputs such that the subscript numbers 1,2,...,7 represent, respectively, energy, wood residue, pulpwood, non-wood materials, production labour input, administration workers, and capital. The β_m's are the first order coefficients for the outputs where the subscripts 1,2,...,6 represent net output of wood pulp, newsprint, paper other than newsprint, paperboards and building boards, BOD and TSS, respectively.

[9] For concavity all eigenvalues should be non-positive.

[10] For quasi-concavity BH2, BH4, BH6 $\geq 0 \geq$ BH1, BH3, BH5.

3.7 References

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CHAPTER 4 Environmentally Sensitive Nonparametric Analysis of Economic Performance

4.1 Introduction

This study proposes and implements nonparametric techniques for environmentally sensitive analysis of economic performance. The techniques are applied to analyze productivity trends in the Canadian pulp and paper industry. Two major water pollutants from the industry (BOD and TSS) are identified along with desirable outputs and inputs for the analysis.

The proposed primal and dual approaches are based on modifications to the Varian-Banker-Maindiratta inner and outer nonparametric technology bounds as extended by Chavas and Cox (1994) to incorporate technical change. The modified inner nonparametric technology bound requires only input and output quantity data and allows for the presence of pollutant outputs that are not freely disposable. Producer shadow prices for biological oxygen demand (BOD) and total suspended solids (TSS) obtained from the input distance function analysis in Chapter 3 are used in the construction of the outer nonparametric technology bound.

The chapter is organized as follows. The next section introduces nonparametric approaches to productivity analysis in general and outlines some relevant efficiency concepts. The section also presents the modified inner and outer technology bounds proposed for incorporating undesirable outputs into the analysis. An effective quantities approach for recognizing technical change in nonparametric analysis using time series data is discussed in the third section. The data on which the analysis in this chapter is based are described in the fourth section. The results from the implementation of the effective quantities approach to nonparametric production analysis are presented and discussed in the fifth section of the chapter. The last section briefly summarizes and concludes the chapter.

4.2 Nonparametric Methods for Efficiency Analysis

4.2.1 Introduction

Approaches to efficiency measurement fall into two broad categories – parametric and nonparametric. The parametric approach starts with a postulated functional form for the production function or some dual representation of the technology (almost always using a cost or profit function). The parameters of this function are then econometrically estimated by minimizing some function of the deviations of the observed data from the estimated function. The fundamental shortcoming of this approach is that the maintained hypothesis of parametric form can neither be theoretically substantiated nor directly statistically verified. In short, the assumption of parametric form must be "taken on faith" (Varian 1984, p. 579).

Nonparametric approaches, on the other hand, do not, explicitly or implicitly, impose *a priori* or *ad hoc* restrictions on the underlying technology.[1] This flexibility is the most important advantage of the nonparametric approach to production analysis. For example, the production possibility set Y, i.e.

$$Y = \left\{ (u, x) \middle| x \ can \quad produce \quad u \right\}$$

where x and u are input and output vectors, respectively, can be expressed nonparametrically as a piece-wise frontier without assuming a functional form for the technology. This representation of the technology can then be used as a reference for gauging the economic performance of a given observation.

4.2.2 Efficiency Measurement Concepts

Efficiency can be broadly defined as the degree to which a desired set of effects are achieved (Fare, Grosskopf and Lovell 1985). The level of efficiency is then measured using some index for comparing observed with desired performance. This comparison may be made in terms of quantities (inputs and outputs) or values (cost, revenue, and profit). Efficiency can also be decomposed into a number of components.

The efficiency measures or indexes that are most frequently used in modern efficiency literature were originally proposed and applied in Farrell (1957), which is by far the most influential work in frontier efficiency analysis. Farrell drew upon and extended, through the addition of price dependent efficiency aspects, measures proposed earlier by Debreu (1951) and Koopmans (1951). Farrell proposed that the overall efficiency of a firm can be decomposed into two components: technical efficiency and allocative efficiency. Technical efficiency measures the ability of the firm to produce a given set of outputs with the minimal set of inputs, given the state of the production technology. Allocative efficiency ("price efficiency" in Farrell's terminology) measures the ability of the firm to use the optimal (cost minimizing) mix or proportion of inputs. Economic efficiency (or "overall efficiency" in Farrell terminology) combines the above two measures of efficiency and reflects the ability of the firm to minimize the cost of producing a given vector of outputs.

The efficiency measures defined above are illustrated in Figure 4.1 using a piece-wise linear input frontier or isoquant constructed using observations R, S, T and W which use different input vectors to produce the output vector *u*.

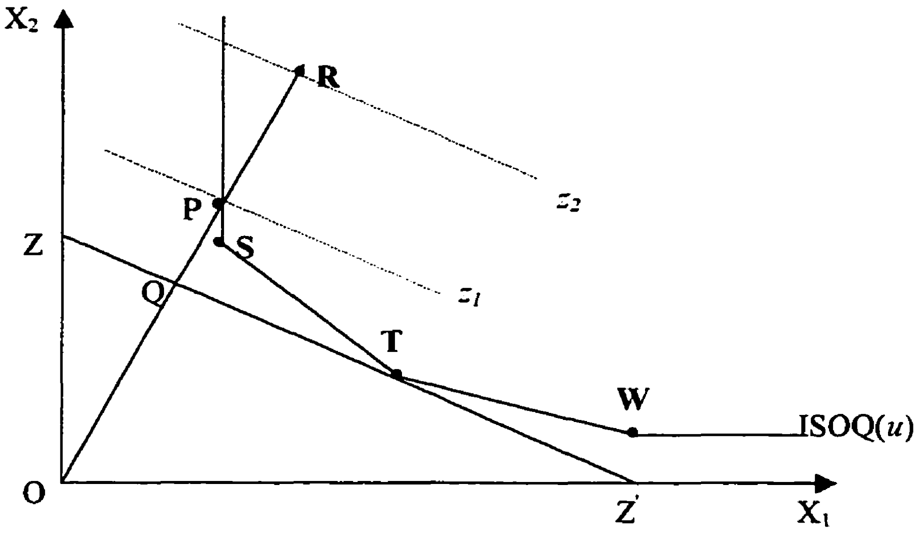


Figure 4.1 Input-Oriented Technical and Allocative Efficiency

Firms S, T and W are all on the frontier and technically efficient in the sense of Farrell. The input-oriented technical efficiency (TE) of firm R is measured by the ratio:

$$TE^R = \frac{OP}{OR}$$

This measures the proportion by which the input vector utilized by R can be scaled down, without any reduction in the vector of outputs produced. It is the ratio of the smallest feasible radial contraction of the input vector of firm R to the actual input vector utilized by this firm.

For the prevailing ratio of input prices, which is given by the slope of the isocost line ZZ', the optimal mix of inputs for producing output vector *u* is achieved at T. The allocative efficiency (AE) of firm R is equal to:

$$AE^{R} = \frac{OQ}{OP}$$

which indicates the extent to which cost could have been reduced by a reallocation of input costs from the technically (but not allocatively) efficient input vector at P to the technically and allocatively efficient input vector at T. This is simply the ratio of the isocost lines through points T and P. Similarly, the ratio of the isocost lines through T and R indicates the overall or economic efficiency of the firm, which reflects the reduction in costs that would occur if production took place at T instead of at R. Economic efficiency is equal to the product of technical and allocative efficiency:

$$EE^{R} = \frac{OQ}{OR} = \frac{OP}{OR} . \frac{OQ}{OP} = TE^{R} . AE^{R}$$

In practice, allocative efficiency is computed as a residual by dividing economic by technical efficiency as discussed below. Given a piece-wise representation of the production technology Y, the technical efficiency measure for a firm i utilizing a set of inputs, x_i, to produce a vector of outputs u_i, is computed by solving the following mathematical programming problem to search for the maximum equiproportionate reduction in the vector x_i that is consistent with the continued production of the vector u_i:

$$TE^{i} = Min_{\theta} \left\{ \theta : \left(u_{i}, \theta x_{i} \right) \in Y, \; \theta \in R^{+} \right\} \qquad (4.1)$$

In other words, this Farrell measure of technical efficiency is equal to the reciprocal of the value of input distance function (Shephard 1953, 1970). Similarly, the relevant value of the cost function for this firm is computed as follows, using mathematical programming to search for an input vector that minimizes the cost of producing the output vector , subject to the existing technology and input prices:

$$C(p_i,u_i) = Min_x\{p_i'x : (u_{I,}x)\in Y\} \qquad (4.2)$$

where p_i is the vector of input prices that the firm is facing. Then the ratio of the minimum cost to the cost of the actual set of inputs utilized by the firm, $p_i'x_i$, gives the measure of economic efficiency:

$$EE^i = \frac{C(p_i,u_i)}{p_i'x_i} \qquad (4.3)$$

The measure of allocative efficiency for firm *i* is then obtained from TE^i and EE^i:

$$AE^i = \frac{EE^i}{TE^i{}_i} \qquad (4.4)$$

The Farrell efficiency measures defined above and used in our empirical analyses are known as *radial* efficiency measures because technical efficiency is computed relative to the proportionally (or radially) smallest feasible input vectors.[2] Radial measures have several features that make them attractive for empirical analyses (Fare *et al* 1985; Lovell 1993; and Coelli, Rao and Battese 1998). First, they are easy to compute as the proportion of inputs is constrained to remain the same for the calculation of technical efficiency. Second, they are invariant with respect to the units with which inputs are measured. Third, these efficiency measures have straightforward cost interpretations. For example, the values (1-TE), (1-AE) and (1-EE) measure the proportional cost savings that can be achieved by the elimination of technical, allocative, and both technical and allocative inefficiency, respectively. Fourth, these measures are multiplicatively decomposable. Finally, the technical efficiency measure is equivalent to (the reciprocal of) the input distance function value and can be used in the computation of Malmquist productivity indexes.

However, radial measures may lead to an overstatement of the level of efficiency by ignoring input slacks or excesses such as the segment PS in Figure 4.1 when the input isoquant has sections that run parallel to the axes.[3] Four things can be noted about this shortcoming (Coelli, Rao and Battese 1998). First, there are no simple and simultaneously unit invariant methods for incorporating slacks in the technical efficiency measure. Second, the importance of such slacks may be overstated in practice; slacks occur only on the horizontal or vertical extremes of the frontier. Third, slacks may essentially be looked at as allocative rather than technical efficiency (Ferrier and Lovell 1990). Finally, slacks can be reported along with the radial measures.

4.2.3 Construction of Nonparametric Technology Frontiers

4.2.3.1 Technology Sets without Undesirable Outputs

Although Farrell (1957) illustrated his different efficiency measures using a nonparametric or piece-wise linear convex unit isoquant[4] which he constructed using agricultural data from 48 US states, the nonparametric approach to efficiency analysis was rarely used in the two ensuing decades, the exceptions being Boles (1966) and Afriat (1972). The turning point came with the publication of a paper by Charnes, Cooper and Rhodes (1978) (CCR) introducing an increasingly popular nonparametric method known as data envelopment analysis (DEA) in the management science/ operations research literature. DEA involves the use of mathematical programming to construct a nonparametric piece-wise linear frontier that "envelops" the observed data. Banker, Charnes, and Cooper (1984) (BCC) proposed a variable returns to scale (VRS) version of the (CCR) model. The BCC DEA is the same as the inner bound technology set used in nonparametric production analysis in economics.

In the economics literature, Varian (1984), building on the work of Afriat (1972) and Hanock and Rothchild (1972), shows how nonparametric bounds for the underlying technology can be constructed if the observed data are consistent with profit maximization. In other words, Varian's approach requires that *all* the observed data be consistent with his Weak Axiom of Profit Maximization (WAPM) condition. Banker and Maindiratta (1988) introduce the concepts of *weak rationalization* and extend Varian's approach to cases where, because of firm technical or allocative inefficiency, the data may not be rationalizable in the sense of Varian (or *strongly rationalizable*). Banker and Maindiratta's tightest inner bound technology set is the same as Varian's. Their outer bound, however, differs from Varian's in that it excludes observations that fail the WAPM test.

4.2.3.2 Technology Sets with Undesirable Outputs

The nonparametric approaches by Varian (1984) and Banker and Maindiratta (1988) as well as the approaches by Chavas and Cox (1994) and Chavas, Aliber and Cox (1994), discussed later in this section, all assume that outputs are desirable and freely disposable. Their approaches do not acknowledge the presence of undesirable (pollutant) outputs. Since pollution abatement is an activity that consumes scarce resources, the exclusion of undesirable outputs leads to distorted measures of economic performance of firms and a distorted sense of economic progress over time. In particular, firms or periods with higher pollution abatement activities will appear inefficient or less productive, relative to other firms or periods if the conventional nonparametric specifications are used.

These nonparametric approaches can be modified to incorporate undesirable outputs into the analysis. Suppose the production process in an industry employs N inputs to produce M outputs. Let

$x \in \Re_+^N$, $p \in \Re_+^N$ $u \in \Re_+^M$, $r \in \Re^M$ denote vectors of inputs, input prices, outputs, and output (market and shadow) prices, respectively[5]. Start with observed input and output quantity and price data for a set $\mathcal{T}$ of T firms. Suppose further that a subvector *v* of outputs is desirable while the remaining subvector *w* of u is a vector of "bads" or pollutant outputs. The purpose is then to construct nonparametric bounds for the underlying production technology.

This requires specifying the minimum requirements that a set $Y \subseteq \Re_+^N \times \Re_+^M$ must satisfy in order to qualify as a production possibility set representing the technology underlying the set of observations in $\mathcal{T}$ Following Banker and Maindiratta (1988), we will consider a production possibility set Y *admissible* if it satisfies the following four requirements:

1) Y is closed and convex.
2) For all $j \in \mathcal{T}$, $(u^j,x^j) \in Y$.
3) Y rationalizes the subset of observations $\mathcal{I}=\{i: \Delta_i=0\} \subseteq \mathcal{T}$ where the criterion function Δ is defined by $\Delta_i = \max\ \{(r^i u^j - p^i x^j)-(r^i u^i - p^i x^i),\ i, j \varepsilon \mathcal{T}\} \geq 0$. In other words, we have $r^i u^i - p^i x^i \geq r^i u - p^i x$, for all $(u,x) \in Y$ and for all $i \in \mathcal{I}$
4) If $(v,w,x) \in Y$ and $v \geq v'$, $w' \geq w$, $x' \geq x$, then $(v',w',x') \in Y$.

Closure and convexity are basic regularity conditions that are customarily imposed on the production possibility set. Closure is customarily imposed, at no cost, because it ensures that the extrema for optimization problems such as those in equations (4.1) and (4.2) above are part of the technology. The convexity of the production possibility set is commonly assumed for reasons of analytical convenience. With the convexity assumption standard linear programming can be used to compare the efficiency of any observation against a linear or convex combination of an efficient subset of observations.

The justification for the second requirement is obvious; we want the constructed technology to include (or support as feasible) all the empirically observed input-output combinations we have in the sample. The third condition is Banker and Maindiratta's (1988) concept of *weak rationalization*. The subset $\mathcal{E}$ (of $\mathcal{T}$) consists of the observations that are consistent with Varian's WAPM condition. The condition in (3) requires that the production possibility set rationalize this subset of efficient observations to qualify for admissibility.

The fourth requirement, which is different than that of Banker and Maindiratta, is for the monotonicity conditions that we have modified to incorporate undesirable outputs into the specification of the production technology. As in conventional analysis, desirable outputs and inputs are assumed to be freely disposable. But a reduction in pollutant outputs requires the diversion of inputs from the production of desirable outputs for abatement purposes. In other words, it requires the use of additional inputs, other outputs remaining the same; or it requires sacrificing desirable outputs if the reduction in undesirable outputs is to be achieved without the consumption of additional input resources. Therefore, pollutants can essentially be treated like inputs into the production process for the purpose of our analysis. This feature of undesirable outputs is reflected in the fourth admissibility condition above. Our proposal for the treatment of undesirable outputs in the same fashion as inputs is similar to a suggestion made by Haynes *et al* (1995) in the context of DEA type formulations for measuring relative efficiency in pollution prevention activities. Haynes *et al* (1995) focus on measuring efficiency in pollution control; but their approach can be extended for the purpose of measuring productive efficiency.

The following two production possibility sets provide, respectively, the tightest inner and the tightest outer bounds to the set of admissible technology sets satisfying conditions (1) to (4) described above (Banker and Maindiratta 1988):

$$EYI = \left\{ (v,w,x) \middle| v \le \sum_{i \in \mathcal{S}} z^i v^i, w \ge \sum_{i \in \mathcal{S}} z^i w^i, x \ge \sum_{i \in \mathcal{S}} z^i x^i, \sum_{i \in \mathcal{S}} z^i = 1;\ v,w,x,z^i \ge 0; i \in \mathcal{S} \right\} \tag{4.5}$$

$$EYO = \left\{ (v,w,x) \middle|\ r^i v + r^{*i} w - p^i x \le r^i v^i + r^{*i} w^i - p^i x^i;\ i \in \mathcal{S};\ v,w,x \ge 0 \right\} \tag{4.6}$$

where z^i is the weight assigned to firm or observation i in construction of the DEA frontier and r^{*i} represents the vector of pollutant shadow prices for firm or observation i. In other words, for any admissible production possibility set Y we have $EYI \subseteq Y \subseteq EYO$. The inner technology bound EYI is the convex hull of the observations in $\mathcal{S}$ and as such is the smallest convex set enveloping these data.[6] It also satisfies the other three conditions for admissibility. Similarly, the outer bound EYO satisfies all four conditions, and it includes any set that is admissible as a production possibility set because the only restriction on the outer bound is that it rationalize the elements in $\mathcal{S}$. It follows from these results that the technical efficiency and the overall cost efficiency measures from the inner and outer bounds provide, respectively, the upper and lower bounds to the technical and overall cost measures for a given observation evaluated over all admissible sets. See Banker and Maindiratta (1988) for more details on these results.

In the discussion below, we will alternatively refer to the inner and outer technology bounds as the primal (inner) and the profit dual (outer) bound to emphasize the nature of their construction; the first makes no behavioural assumption while the latter is based on the postulate of profit maximization. The technology bounds required for conventional (i.e. without pollutant outputs) productivity analysis are obviously special cases of those in equations (4.5) and (4.6); and we will refer to the conventional bounds corresponding to the EYI and EYO as YI and YO, respectively.

The construction of the inner and outer technology bounds is illustrated in Figure 4.2 using four observations from a one input, one output production process. The four observations are the firms operating at points A, B, C, and D. The inner technology bound YI from would then be given by the double line segments connecting points K, A, C, and D and extending horizontally to the right of point D. The input-output combinations on this inner bound and to the left and below it make up the smallest negative monotonic convex hull that includes all the observations. Firms A, C, and D are operating on the frontier while firm B is technically inefficient.

The outer bound YO is formed from the boundary of the intersection of the half spaces created by the profit hyperplanes or isoprofit lines for the firms that satisfy the WAPM condition, i.e. firms A, C, and D in this case. This outer bound is marked by the heavy line passing through points O, M, E, F, and S in Figure 4.2.

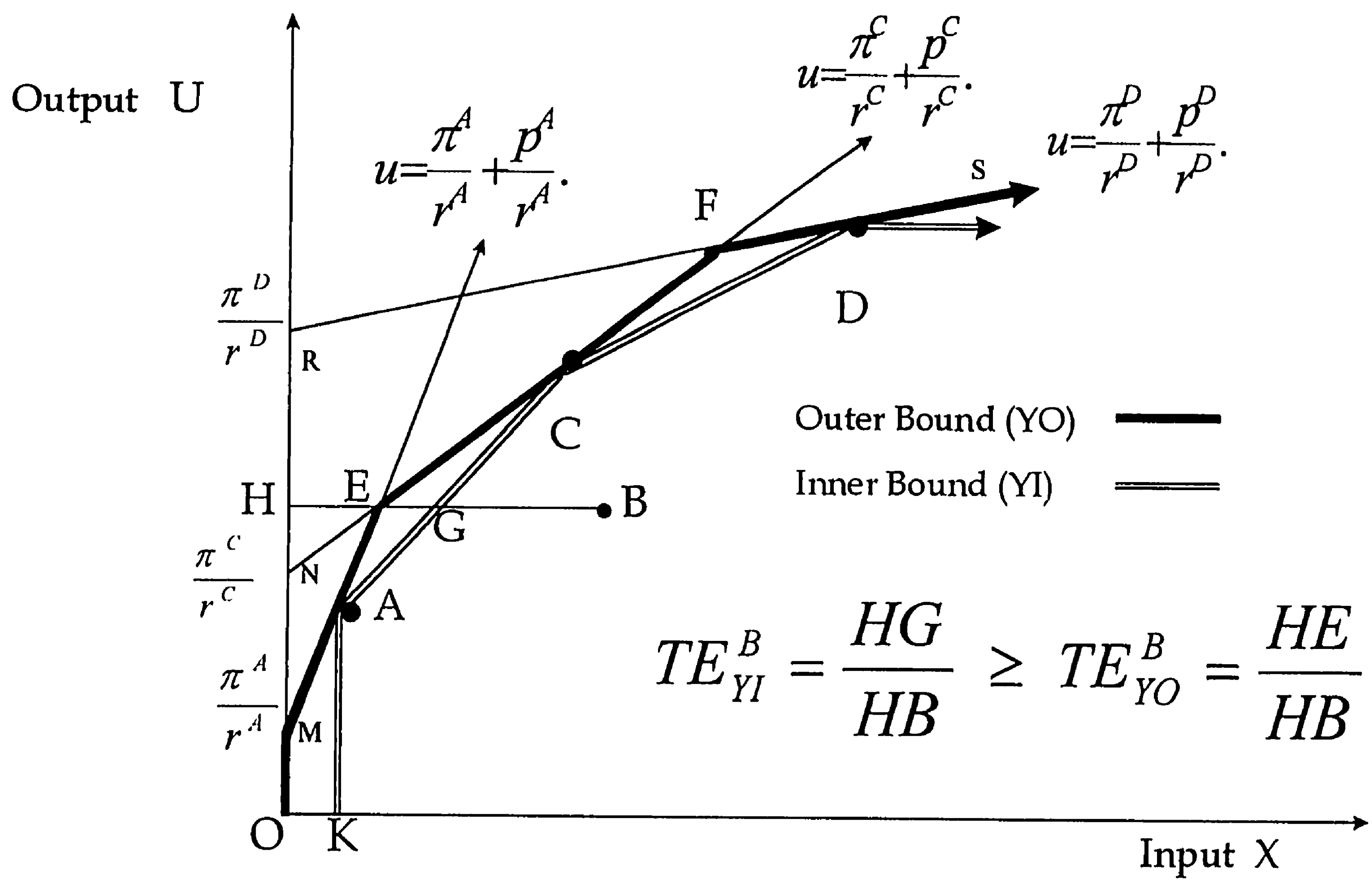


Figure 4.2 Illustration of Inner and Outer Nonparametric Technology Bounds

While primal nonparametric or DEA representations of the technology have been modified in several studies to allow for undesirable outputs,[7] we are not aware of any study that has employed dual nonparametric methods for the purpose of environmentally sensitive analysis. This is mainly due to practical rather than conceptual difficulties. The problem lies in finding reliable estimates of pollution damages or the benefits of pollution abatement that can be as pollutant prices in the construction of the outer nonparametric bound.

In this study, we use the BOD and TSS shadow prices or abatement cost estimates obtained from the input distance function analysis in Chapter 3 as prices for these pollutants in the construction of the outer technology bound. Whether these prices are below or above the pollution damage values depends on whether abatement is carried out at below or above the socially optimal levels. If we assume that pollution abatement was below optimum levels for most of the periods covered in the study, then our estimates understate the benefits of pollution reduction. Under such circumstances the environmentally sensitive measures of productivity growth we derive in this chapter are likely to be lower than the true rates.

4.3 Technical Change and Nonparametric Analysis

The techniques discussed above are ideal for cross-section efficiency analysis, or for analysis panel data from which both efficiency and technical change can be separately identified.[8] When only time series data for a single economic entity is used, however, changes in both technical efficiency and technical change have to be dealt with simultaneously.

There are two alternative ways to deal with the problem created due to technical change over time (Chavas and Cox 1994). One solution is to adopt an "intertemporal" view of the production technology and interpret the efficiency scores computed with reference to the technology as combined efficiency and technical change scores. Since all observations are judged against the same "intertemporal" frontier or reference technology, the computation of productivity index series is a straightforward exercise, after a preferred base period has been chosen.

This intertemporal approach to technical change has some important shortcomings, however. It is possible that a large number of data points or observations in the time series might fail the WAPM test because of inefficiency and/or technical change that occurs over time. Under such circumstances, the subset $\mathcal{E}$ out of which the Banker-Maindiratta outer bound is to be constructed can have too few observations. In the extreme case, the efficient $\mathcal{E}$ might be empty or it might have only one observation resulting in a perfectly flat outer technology bound.

To overcome this problem, Chavas and Cox (1994) propose an alternative approach based on the concept of "technical augmentation" to deal explicitly with technical change in the model. Technical change modifies the effectiveness of inputs and outputs. The relationship between effective inputs and effective outputs remains the same throughout the period of study. But the relationship between effective quantities and actual quantities changes with technology. It is hypothesized that technical change "augments" actual quantities (x_t,v_t, w_t) into "effective quantities" denoted by (X_t,V_t, W_t) according to the following one-to-one increasing functions:

$$X_{nt} = X(x_{nt}, A_{nt}), \qquad V_{mt} = V(v_{mt}, B_{mt}), \qquad W_{kt} = W(w_{kt}, C_{kt}) \qquad (4.7)$$

where: $\mathcal{T}$ is now the set representing the time series; $t \in \mathcal{T}$ indexes the time period; $n = 1,\dots,N$, indexes inputs; $m = 1,\dots,d$ indexes the d desirable outputs and $k = (d+1),\dots,M$ indexes M-d undesirable outputs; and the A_t's, B_t's and C_t's are period t technology indexes that augment the actual quantities of inputs (x), desirable outputs (v) and undesirable outputs (w) into effective quantities. Following Chavas and Cox (1994), we adopt a translation hypothesis for the relationship between effective and actual quantities, i.e.

$$X_{nt} = x_{nt} - A_{nt}, \qquad V_{mt} = v_{mt} + B_{mt}, \qquad W_{kt} = w_{kt} + C_{kt} \qquad (4.8)$$

The Chavas-Cox methodology has the additional advantage that the changes in the technology indexes can be interpreted in terms of technical change bias (Chavas *et al* 1994). An increase (decrease) in the technology index for the *n*-th input, A_{nt}, implies technical change that is *n*-th input-using (input-saving) because the production of the same effective inputs requires the use of more (less) of the actual input with the technical change. For desirable outputs, an increase (decrease) in the technology index of the m-th output corresponds to technical change that is m-th output-reducing (output-augmenting). The opposite is true in the case of undesirable outputs because the technology indexes C_{it} are restricted to be non-positive as discussed below.

The technology indexes are computed by minimizing some function of these technology indexes, subject to the following conditions: 1) technology indexes for inputs and desirable outputs are positive and the technology indexes for undesirable outputs are negative; 2) all effective quantities are non-negative; and 3) effective quantities satisfy the WAPM condition. In our case, the technology indexes were estimated by minimizing the sum of the absolute values of the ratios of the technology indexes to their respective actual quantities.[9] Therefore, the following linear programming problem was solved to compute the technology indexes:

$$Min_{A,B,C} \quad \sum_{T\in\mathscr{T}} \left\{ \sum_{n} \frac{A_{nt}}{x_{ntr}} + \sum_{m} \frac{B_{mt}}{x_{nmr}} + \sum_{k} \frac{C_{kr}}{x_{kr}} \right\} \tag{4.9}$$

$$Subject \quad to: \quad r^{t}V^{t} + r^{*t}W^{t} - p^{t}X^{t} \geq r^{t}V^{s} + r^{*t}W^{s} - p^{t}X^{s} \tag{4.10}$$

$$and$$

$$A_{t}, B_{t}, C_{t}V, W, X \geq 0; \quad s, t \in \mathscr{T} \tag{4.11}$$

This formulation of the technology index estimation problem makes it clear that the effective technology obtained can be interpreted as the minimum perturbation to the observed data required to satisfy WAPM at all data points. The outer and inner bounds based on the effective quantity approach include all observations, whether they are expressed in effective or actual quantities. This is implied by the monotonicity condition discussed in the previous section above together with the fact that $v_t \leq V_t$, $w_t \geq W_t$ and $x_t \geq X_t$ because the technology indexes are restricted to be non-negative for desirable outputs and inputs and non-positive for undesirable outputs.

To summarize our discussions so far, the inner and outer bounds under the effective quantity approach are represented by the following two sets:

$$EYI^{e} = \left\{ (v,w,x) \middle| \, v \leq \sum_{i\in\mathscr{T}} z^{i}V^{i}, w \geq \sum_{i\in\mathscr{T}} z^{i}W^{i}, x \geq \sum_{i\in\mathscr{T}} z^{i}X^{i}, \sum_{i\in\mathscr{T}} z^{i} = 1; \; v,w,x,z^{i} \geq 0; i \in \mathscr{T} \right\} \tag{4.12}$$

$$EYO^{e} = \left\{ (v,w,x) \middle| \; r^{i}V + r^{*i}W - p^{i}X \leq r^{i}V^{i} + r^{*i}W^{i} - p^{i}X^{i}; \; i \in \mathscr{T}; v,w,x \geq 0 \right\} \tag{4.13}$$

These are used as reference technologies for computing efficiency measures under the Chavas-Cox or effective quantities approach to nonparametric analysis of productivity growth. The conventional counterparts to the above technology bounds are obtained as special cases by excluding pollutant outputs from the formulation; we will refer to these bounds as YI^e and YO^e, respectively.

4.4 Data

The data described and used in the previous chapters were used in the nonparametric analysis in this chapter. To simplify the computational burden, however, all desirable outputs were aggregated into one output index. The seven input categories were similarly aggregated into four input indexes. In particular, wood residues, pulp wood and non-wood materials were aggregated into a *Materials* category. Administration and production labour were also combined into one, *Labour*, category of inputs. These aggregations were carried out using the Divisia-Tornqvist index number formula. Thus, for the following analyses, one aggregate desirable output, two pollutants (BOD and TSS) and four inputs (energy, capital, labour and materials) were identified. The BOD and TSS quantities were also indexed by dividing by their respective 1959 values to place all quantities on a comparable scale. Therefore, the base period for all the quantity indexes is 1959.

4.5 Discussion of Results

The mathematical programming problems discussed in section 4.3 were formulated in GAMS and solved to obtain:

1) technology indexes (A, B, and C) from the formulation in equations (4.9) to (4.11), and
2) technical, allocative and economic efficiency scores from the effective quantity technology bounds in equations (4.12) and (4.13), with and without pollutant outputs.

The estimates of technical efficiency scores and the technology indexes are discussed below. Allocative and economic efficiency scores are not required for the construction of productivity growth rates or indexes, and are, therefore, excluded from the discussion below to save space.

4.5.1 Analysis Without Pollutant Outputs

The strongest observable trend in the technology indexes occurs for capital in the period from the mid-1980s to 1991, during which the index for capital has been rising. This indicates capital-using technical change during that period. The other technology indexes showed no discernible trend. Although there were some variations in the technology indexes for materials and labour, the overall trends show that technical change has been neutral with respect to these inputs as well.

These technology indexes were used to transform the actual inputs to effective inputs and the "effective" technology bounds, primal (YI^e) and profit dual (YO^e), were constructed from the effective quantities. These effective technologies were then used as references against which each of the observations in the period from 1959 to1994 were compared. Unlike the case of the intertemporal technology approach discussed above, the profit dual "effective" technology is constructed from all the observations in the sample. This is because all the observations satisfy the WAPM tests in effective quantities by construction.

Estimates of productivity growth derived using the inner technology bound indicate that overall there was little or no productivity growth over the period of the study. This is to be expected given the fact that the inner bound is the tightest technology including the sample of observations and that the efficiency estimates obtained from it constitute the upper bounds on the true efficiency scores. As a tight bound around the data, the inner bound fails to adequately discriminate between efficiency levels of observations.

The results from the outer technology bound, on the other hand, suggest substantial growth in productivity, at 3.9 percent per year over the sample period. Since these are based on the tightest outer bound to the set of admissible technologies, these results are likely to overstate the true productivity changes. To get a better approximation of the true productivity changes, we combined the efficiency estimates from the inner and outer bounds by taking their geometric means.

These combined estimates indicate that productivity growth was positive throughout the period except in 1967, 1970, 1974-75, 1980-82, 1986 and 1989. The early 1990s was once again found to be the period of most rapid improvement in productivity, at the rate of 6.1 percent per year. Productivity growth rates for the 1960s, 1970s and 1980s were estimated to be, respectively, 2.0 percent, 0.3 percent, and 1.1 percent per year. On average, productivity grew at the rate of 1.8 percent per year during the period from 1959 to 1994.

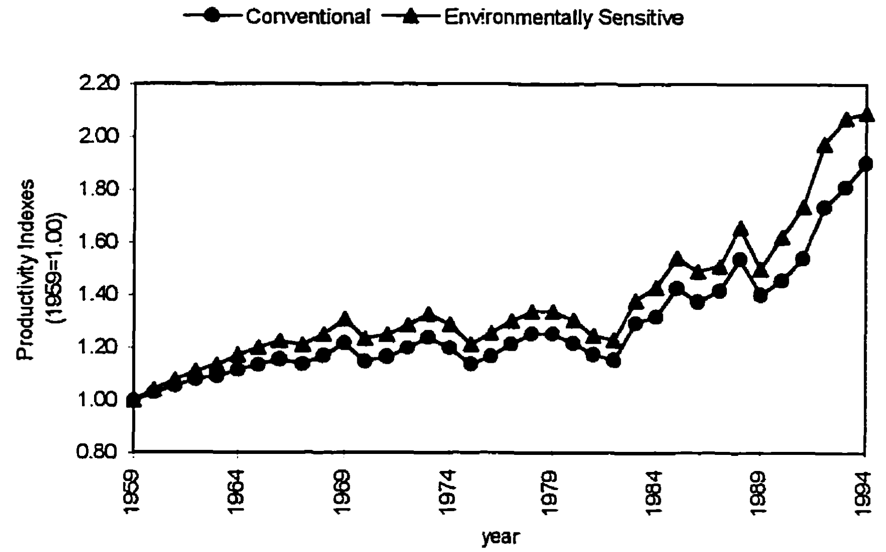
4.5.2 Analysis With Pollutant Outputs

The results obtained when pollutant outputs are incorporated into the analysis confirm the conclusion from Chapter 3 that conventional measures understate the productivity gains in the industry. There is a big gap between the inner and outer bound technology results. There is little change in productivity according to the results from the inner bound, while the outer bound results suggest significant (an average of 7.45 percent per year) increases in productivity. The combined results from the two bounds show that productivity in the Canadian pulp and paper industry grew at a rate of 2.1 percent per year over the study period.

The results concerning the nature of bias of technological change and the periods of negative productivity change are the same as those obtained from the analysis without pollutant outputs. The trends in productivity change over time obtained here are also similar to those obtained in Chapter 3 and the results from the nonparametric analysis ignoring polutants discussed above in this chapter. Productivity growth slows down from 2.7 for the 1960s to only 0.2 percent in the 1970s and rises to 1.1 percent per year in the 1980s before jumping to 6.6 percent per year for the early 1990s. The rapid increase in the 1990s was explained in Chapters 2 and 3 as a result of a combination of factors that led to a higher proportion of new mills equipped with modern technologies.

The productivity indexes, conventional as well as environmental, are plotted in Figure 4.3. Table 4.1 contains more detail on the results from both the conventional and environmentally sensitive nonparametric approaches discussed here.

Figure 4.3
Productivity Indexes from Analysis with Nonparametric Technology in Effective Quantities



4.6 Summary and Conclusion

The study proposed modifications for incorporating pollutant outputs into nonparametric analyses of productivity and efficiency. These methods were implemented using an effective quantity approach for recognizing technical change in nonparametric analysis.

Although nonparametric analysis is attractive because it avoids imposing restrictive functional forms for the technology, the gap between the inner and outer nonparametric bounds can be large making it difficult to "pin down" the nature of the underlying technology. In both the analyses with and without pollutant outputs, there was a large gap between the results from the inner and outer technology bounds. The inner technology bounds generally indicate little or no productivity change in all cases. This is to be expected because these bounds are the tightest inner bounds to the technology and the observed data. As a result, the inner technology bounds discriminate little between the different observations. The outer technology bounds, on the other hand, indicate substantial or large productivity increases over time. Geometric means of the productivity estimates from the inner and outer bounds were used to approximate the unknown true productivity levels.

Technical change was neutral with respect to almost all inputs. There were no signs of energy or labour saving bias. Technical change was capital-using in the mid to the late 1980s. Although lack of signs of labour-saving bias in the results may look surprising, this is not the first study to report such findings. For the variety of the findings, see Constantino and Haley (1985).

The results in this chapter indicate that productivity changes, as measured in environmentally sensitive ways, have been increasing faster than most conventional studies to date have indicated. In our study, the environmentally sensitive productivity percentage growth rate estimate was 0.30 points higher than the conventional measures. These confirm the conclusion from Chapter 3 that productivity in the Canadian pulp and paper industry has been rising faster than is suggested by measures that ignore changes in the industry's pollution output

Table 4.1. Productivity in the Canadian Pulp and Paper Industry: Results from Analysis Using Nonparametric Technology in Effective Quantities

	WITHOUT POLLUTANT OUTPUTS			WITH POLLUTANT OUTPUTS		
year	GEOMETRIC MEAN OF TE SCORES FROM INNER & OUTER BOUNDS	PRODUCTIVITY GROWTH RATES FROM INNER & OUTER BOUNDS	PRODUCTIVITY INDEXES FROM INNER & OUTER BOUNDS (1959=1)	GEOMETRIC MEAN OF TE SCORES FROM INNER & OUTER BOUNDS	PRODUCTIVITY GROWTH RATES FROM INNER & OUTER BOUNDS	PRODUCTIVITY INDEXES FROM INNER & OUTER BOUNDS (1959=1)
1959	0.52	...	1.00	0.47	...	1.00
1960	0.54	3.0%	1.03	0.49	4.2%	1.04
1961	0.55	2.6%	1.06	0.51	3.4%	1.08
1962	0.57	2.3%	1.08	0.53	3.0%	1.11
1963	0.57	1.0%	1.09	0.54	2.3%	1.14
1964	0.58	2.2%	1.12	0.56	3.2%	1.17
1965	0.59	1.8%	1.14	0.57	2.2%	1.20
1966	0.60	1.7%	1.16	0.58	2.1%	1.23
1967	0.60	-1.5%	1.14	0.57	-1.3%	1.21
1968	0.61	2.7%	1.17	0.59	3.4%	1.25
1969	0.64	3.9%	1.22	0.62	4.7%	1.31
1970	0.60	-5.9%	1.15	0.58	-6.1%	1.23
1971	0.61	1.4%	1.17	0.59	1.2%	1.25
1972	0.62	2.6%	1.20	0.61	2.9%	1.29
1973	0.64	3.4%	1.24	0.63	3.3%	1.33
1974	0.62	-3.3%	1.20	0.61	-3.1%	1.29
1975	0.59	-5.0%	1.14	0.57	-6.2%	1.21
1976	0.61	2.5%	1.17	0.59	3.7%	1.26
1977	0.63	3.8%	1.21	0.61	3.6%	1.30
1978	0.65	3.2%	1.25	0.63	2.8%	1.34
1979	0.65	0.0%	1.25	0.63	0.0%	1.34
1980	0.63	-2.9%	1.22	0.61	-2.7%	1.31
1981	0.61	-3.6%	1.18	0.58	-4.6%	1.25
1982	0.60	-1.9%	1.15	0.58	-1.3%	1.23
1983	0.67	11.5%	1.30	0.64	11.7%	1.38
1984	0.68	1.9%	1.32	0.67	3.4%	1.43
1985	0.73	7.9%	1.43	0.72	7.6%	1.54
1986	0.71	-3.7%	1.38	0.69	-3.5%	1.49
1987	0.73	2.9%	1.42	0.70	1.4%	1.51
1988	0.79	8.3%	1.54	0.76	9.2%	1.66
1989	0.71	-9.4%	1.40	0.69	-9.9%	1.50
1990	0.74	3.8%	1.46	0.74	7.6%	1.62
1991	0.78	5.8%	1.54	0.79	7.0%	1.74
1992	0.88	11.7%	1.74	0.90	12.8%	1.97
1993	0.91	4.3%	1.81	0.94	4.9%	2.07
1994	0.96	5.0%	1.90	0.95	0.9%	2.09
AVERAGES:						
1959-69	0.58	2.0%	1.11	0.55	2.7%	1.16
1970-79	0.62	0.3%	1.20	0.60	0.2%	1.28
1980-89	0.69	1.1%	1.33	0.66	1.1%	1.43
1990-94	0.85	6.1%	1.69	0.86	6.6%	1.90
1959-94	0.66	1.8%	1.28	0.64	2.1%	1.37

NOTES

[1] We include "implicitly" because the choice or use of an index number approach implies some underlying parametric form for the technology (Diewert 1976). Thus analysis using index numbers is inherently parametric, although it is also referred to as "nonparametric" because it does not involve the estimation of parameters.

[2] Output-based efficiency measures can also be defined in very similar ways as indicated above. In this study the focus is on input-based measures because we want to retain a consistent measure for comparing performance estimates with and without pollutant outputs. The two measures are related in a simple way. The output-based measure of technical efficiency will be higher (lower) than the input-based measure of technical efficiency if the production technology is characterized by decreasing (increasing) returns to scale. The two measures are equal only under constant returns to scale (Fare *et al* 1985).

[3] Koopman's (1951) suggested measure of technical efficiency is stricter than Farrell's (1957) and Debreu's (1951) in the sense that it requires both operation at the frontier and absence of slacks.

[4] For a scalar output and with the assumption of constant returns to scale, the unit isoquant provides a convenient common reference for comparing firms regardless of the relative sizes of their inputs and outputs.

[5] The output price vector $r \varepsilon \Re^M$ is not restricted to the non-negative orthant to allow for the presence of pollutant outputs with negative prices.

[6] This is an elementary result from convex analysis; any convex set that contains the observations will have the above convex hull as a subset.

[7] For example, this is followed in the Haynes *et al* (1995) study cited above. Fare *et al* (1989) modify the primal inner bound YI to allow for the free disposability of inputs and desirable outputs but only weak disposability of the output vector. Weak disposability appropriately recognizes the fact that the production of less pollutants involves giving up some desirable outputs or using more inputs. However, the theoretical or empirical justification for this particular approach is seldom clearly stated. There are two more problems with the practical implementation of the weak disposability formulation. First, the approach can lead to positive pollutant shadow prices. Second, the equality restrictions introduced by the weak disposability assumption makes the mathematical programming problem difficult to solve and the solver may pick the simple solution where the technology bound for firm *k* is constructed from firm *k*'s own data point only, without any information from other observations.

[8] Balk and Althin (1996) is a good recent example of dealing with both efficiency and technical change, using the DEA technique. They define new technical change and productivity indexes that are transitive and apply them using a panel data set of Swedish pharmacies.

[9] Chavas and Cox (1994) minimize the sum of the absolute values of the technology indexes. The sum of these values is not units invariant, although when the data are expressed in quantity indexes for the analysis, as is the case in the Chavas and Cox study, the problem might not be a serious one.

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CHAPTER 5 Summary, Conclusion and Recommendations

This thesis presented the results of three studies that attempt to analyze productivity changes in the Canadian pulp and paper industry using time series data covering a period of 36 years, from 1959 to 1994. Total factor productivity growth is defined as the sum of technological change and change in the degree of technical efficiency. Both these components are dealt with in an integrated way in the thesis.

The first study (reported in Chapter 2) employed index number approaches to measure both single and total factor productivity for the industry. That study also employed an estimated input distance function and compared the results from the two approaches. The second and third studies (presented in Chapters 3 and 4) have as their major focus the measurement of productivity in environmentally sensitive ways. For this purpose, two major pollutants from the industry, namely, biological oxygen demand (BOD) and total suspended solids (TSS), were incorporated into the analyses along with marketed (desirable) inputs and products of the industry. Parametric input distance functions are used in the second study. The distance function in both the first and the second studies were specified as translog and estimated using linear programming (or goal programming). The third study proposed and implemented new nonparametric techniques that can be used not only for the measurement of productivity growth over time but also for assessing allocative and overall economic efficiency. By explicitly incorporating pollutant outputs and environmental effects into the analysis, the two latter studies address a major shortcoming in conventional approaches to efficiency and productivity analyses. This shortcoming applies as well in most studies that attempt to assess the impact of environmental regulations on productivity growth. The results from the three studies are briefly summarized and compared below.

The single factor productivity indexes indicate that labour productivity, which is the most common measure of partial productivity, grew faster (at 2.64 percent a year) than any of the remaining single factor measures. Between 1959 and 1994, the productivity of labour had increased by a two and a half times. The productivity of energy inputs also increased, albeit slowly, at an average annual percentage rate of 0.09 over the period. But the partial productivity levels for wood residue, non-wood material and capital inputs declined. Because of improvements in the productivity of pulpwood, however, the productivity of total wood (virgin fibre) inputs increased at the rate of 0.30 percent a year.

Total factor productivity growth estimates obtained from the different methods and approaches are summarized below. The conventional measures (i.e. the ones that do not account for pollutant outputs) from both the index number and the input distance function analyses imply that the improvement in the productivity of the industry has been slow. In addition, the results indicate that most of the productivity growth estimated using index number procedures is mainly due to output expansion effects, rather than improvements in efficiency and technical progress.

The industry returns to scale estimates from the input distance functions, with and without pollutant outputs, indicate increasing returns to scale in production. Our average returns to scale estimate was 1.27. This estimate is, however, lower (and, arguably, more plausible) than those reported in several previous studies on the Canadian pulp and paper industry.[1]

Table 5.1. Summary of Annual Percentage Productivity Growth Averages from Different Approaches: Canadian Pulp and Paper Industry, 1959-94

Type of Productivity Measure	Conventional	Environmental
Tornqvist Index	0.41	...
Malmquist Index Based on Tornqvist Index	-0.06	...
Malmquist Index Based on Input Distance Function	0.19	1.00
Nonparametric Analysis in Effective Quantities	1.80	2.10

Productivity growth estimates from the nonparametric techniques are considerably higher than those obtained from the input distance or index number studies. The inner nonparametric bounds show little or no change in productivity while the estimates from the outer nonparametric bounds suggest substantial improvement in productivity. The big gap between the two bounds indicates how difficult it is to approximate technologies using parametric forms, even if flexible functional forms are used. Chavas and Cox (1994) also observed similar gaps between the two bounds in their analysis of productivity in US agriculture.

The figures from both nonparametric and parametric approaches unambiguously show that productivity measures that ignore pollutant outputs substantially underestimate the performance of the industry. Our environmentally sensitive estimates from the input distance function approach indicate that the total factor productivity of the industry has been growing at the rate of 1.00 percent a year, considerably higher than the estimate of 0.19 percent per year obtained from the same analysis ignoring pollutant output reductions. The environmentally sensitive productivity change estimates from the nonparametric analysis is 2.1 percent a year, higher than the 1.8 percent estimate obtained by ignoring pollutant outputs. The most important conclusion to be drawn from these studies is that productivity improvement measured in environmentally sensitive ways has been stronger than conventional measures would suggest. These results are consistent with results for the US electric power, pulp and paper and agricultural industries obtained by Repetto *et al* (1996, 1997), who employ pollution output damage estimates from non-market valuation studies to compute environmentally-adjusted productivity indexes.

Technical change was found to be neutral with respect to most inputs. There were no signs of energy or labour saving technical change. Technical change was capital-using only in the period from the mid 1980s to 1991. The technical change bias measures discussed here are from the effective quantity approach to nonparametric analysis.

According to the estimates from the input distance function, pollution abatement costs show an increasing trend throughout the period covered in this study. This is primarily due to the substantial amount of investment in pollution abatement and the subsequent reductions in pollution output rates – evidence of the tendency towards diminishing returns to pollution prevention activity. For example, the rate of biological oxygen demand had been reduced from its 1959 level of 102.1 kilograms per tonne of wood pulp produced to only 13.3 kilograms per tonne of pulp by 1994. The rate of total suspended solids had similarly been reduced from 118 kg per tonne of pulp to only 6 kilograms per tonne of pulp over the same period.

Although none of the studies in this thesis included formal tests on the effect of environmental regulation on productivity, some observations that are relevant to the environment-productivity debate discussed in introductory chapter can be made. First, the presence of substantial difference between conventional and environmentally sensitive measures of productivity change implies that the former can be not a good measure of changes in social welfare especially in circumstances where there are policies affecting the way the environment is treated by industries. Both the proponents of the Porter hypothesis and those with the traditional view that environmental regulation retards productivity define productivity changes in conventional ways, by excluding changes in pollutant outputs. Both sides of the debate are using the wrong yardstick. Second, the increasing trend in pollution abatement cost estimates indicates that, at least at the industry level, "cost offsets" due to environmental regulation are not as prevalent as the proponents of the Porter hypothesis suggest. Third, other changes affecting the industry seem to have been relatively more important than changes in environmental regulation in terms of their effects on productivity growth. For example, the early 1990s is a period when environmental regulation on the Canadian pulp and paper industry was strengthened and when the share of pollution abatement in total capital spending increased to 25 percent. But this period was also the period of the most rapid productivity growth mainly as a result of the addition of new mills and the exit of many old mills.

5.1 Recommendations for Further Research

There are at least two ways in which the current research on the pulp and paper industry can be extended. The first relates to the refinement of the results obtained here using provincial and plant level data. The use of such data would allow more flexibility in analytical approaches. But more important, analysis at the provincial and mill levels would provide information that is useful for assessing the differential impact of environmental regulations, the efficiency of existing regulations and the potential benefits of incentive-based instruments. Panel data collected at the mill level can be used to explore cost dual nonparametric approaches that can be carried out without using shadow price estimates for pollutant outputs. While any two observations are comparable under the profit dual nonparametric approach (profit is a common denominator for both), cost dual nonparametric approaches would require a large number of observations producing similar levels of outputs to construct meaningful technology bounds.[2]

The second line of fruitful extension relates to the explicit recognition of the dynamics of adjustment and capacity utilization. As cited in the discussions above, the periods of low estimated productive efficiency in the industry coincided roughly with periods of macroeconomic recessions. It is not clear how significant these effects are, but it is important to estimate these separately in order to get a more accurate picture of "pure" productivity trends in the industry. But it should also be noted that the approach used in this study overcomes a major shortcoming in traditional approaches by explicitly recognizing efficiency along with technical change. In fact, low capacity utilization levels show up as inefficiencies.

Finally, the results consistently show the need for the use of environmentally sensitive measures of economic performance to promote informed public discussion and decision making.

Public agencies should start to publish and make such information available to the public. Statistics Canada and Environment Canada, together with the provincial environmental departments, should increase the availability and accessibility of data on environmental effects or pollution output. Currently such data are difficult to obtain.

NOTES

[1] See, for example, Frank *et al* (1990), Martinello (1985) and Sherif (1983).

[2] Varian's (1984) cost dual nonparametric approach can be easily extended to incorporate pollutant outputs. This method is a viable option, especially since pollution data is becoming more and more available to the public.

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IMAGE EVALUATION
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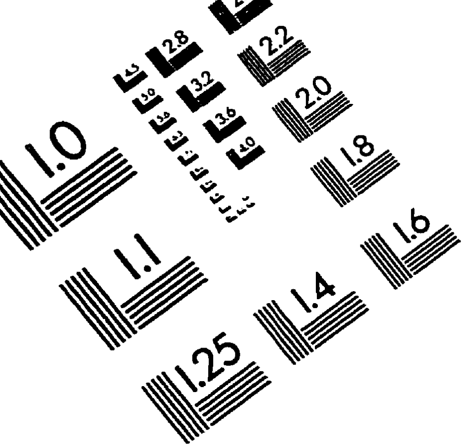

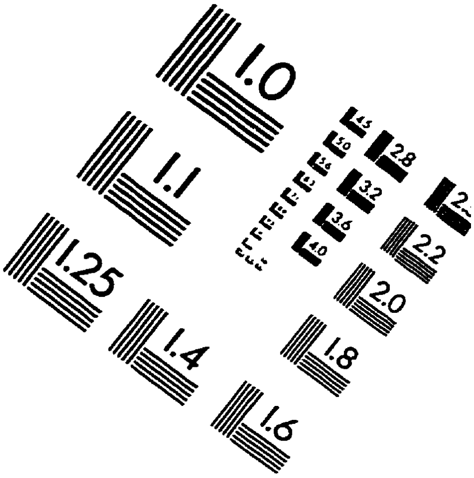

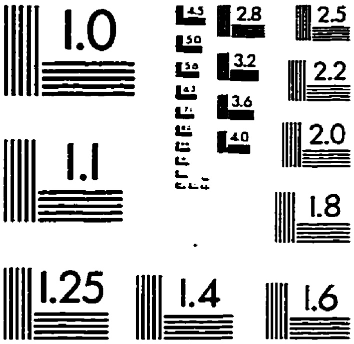

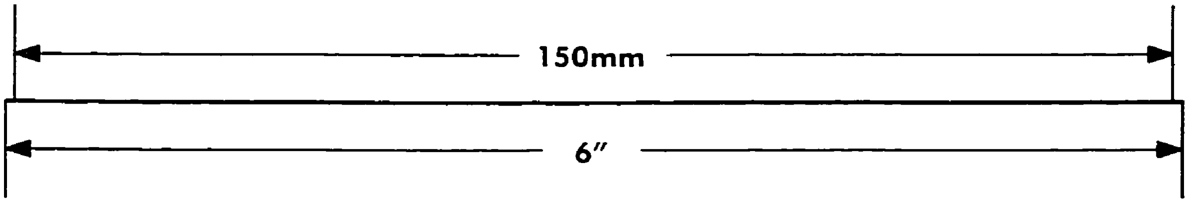

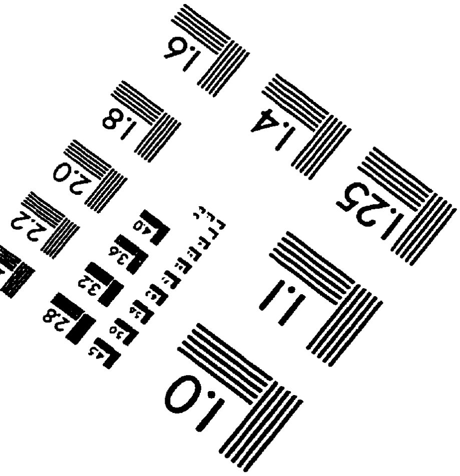

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