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**Production Efficiency and Environmental
Regulations: A Directional Distance
Function Approach**

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ABSTRACT:

Regulations can affect corporate behaviour in various ways, and this paper focuses on environmental regulations designed to limit the pollution of the atmosphere by carbon dioxide emissions. Tremendous debate has been generated regarding the effects of such regulation on firm efficiency and several methods to try and model firm behaviour under those conditions.

Porter (1991) theorised that environmental regulations stimulate corporate innovation, creating a win-win situation for economic and ecological concerns. He pointed out that corporations could identify areas for improvement and take beneficial measures to enhance efficiency. This study models these two concerns to test for a win-win relationship using regression analysis. However, there is no evidence supporting this view.

The primary method in this study was the "Directional Distance Output Function," which models firm technology in a way that captures efficiency by treating output as an increase of the 'desirable' good and a reduction of the 'undesirable' bad.

The test for a win-win relationship was conducted using regression analysis utilising the Directional Distance Output Function efficiency scores and a proxy for the stringency of regulation. This study does not, however, find supporting evidence that greater stringency in regulation was associated with higher firm efficiency. Although it was possible to show missed beneficial opportunities, it was not possible to identify specific areas that needed improvement.

KEYWORDS: Productivity, Environmental Regulations, Porter's Theory, Innovation, Output Distance Function.

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1 Introduction

Humans have had an uneven relationship with nature for a long time. The high living standards among economically wealthy nations have come at the expense of resource and natural exploitation. This exploitative development paradigm has been criticized by some who think that resources and nature are limited and that future generations might be forced to accept lower living standards due to future scarcity and damage to nature. Therefore, the clash between quantitative and qualitative development paradigms is frequent. For instance, while scientists and engineers are concerned about the current massive demand for oil, pollution, growth challenges, and other issues, some economists and politicians, on the other hand, insist on maintaining consumption, high market performance, and technological approaches toward benefiting human conditions.

1.1 Background and Prior Literature.

The views of these two sides are so polarized that there appears to be little progress in easing such conflict (Tilton, 1996). However, there have been some suggestions on how the stalemate can be avoided using a new sustainability paradigm that considers the benefit of both humans and nature or the environment— through sustainable development. Although there seems to be some confusion as to its definition by various parties like ecologists and economists, the World Commission on Environment and Development (1987) explicitly defines it as '...development that meets the demand of the present without the compromise to the ability of future generations to meet their own needs' (Ketola, 2009).

In the face of growing social concern worldwide, social policy has evolved by adapting new regulations in many forms, such as 'traditional command-and-control.' Additionally, economic instruments have been introduced by regional institutions and governments to prevent further environmental damage attributed to exploitative investment activity,

the implementation of pollution caps, pollution permits, and taxes, and even in the form of economic incentives for new 'green technologies' (Similä, 2007).

Preston (1990) reports that management literature considers social responsibility equally crucial in determining long-term organisational success and deserves the same attention as the market environment. Indeed, sustainability has come to the forefront of organisational challenges as individuals and consumers increasingly become aware of the issues lamented by concerned society, thereby demonstrating preference, for instance, for environmentally oriented firms (Winsemius & Guntram, 1992). Organisations have indeed had to adopt "green strategies" through environmentally sensitive policies such as energy conservation, reducing emissions and waste, waste recycling, and new 'green' products (Gifford, 1997).

Dally (1996) alleged that the term 'sustainability' was implemented for the benefit of economic agents, much to the detriment of the natural environment. He explained that the term 'sustainable development' has such an elusive meaning that it is useless. He criticised the current underlying assumptions of macroeconomics as biased towards economic agents. He called for radical changes to embrace economics under the broader environmental scope and consideration of new universal knowledge. The faulty 'old economic premise' in which the factors of production seem to disregard natural capital historically in reports such as Gross National Product needs to be changed. Ketola (1998) also lamented how firms exploited the claim to adopt environmental strategies, much to their short-sighted benefits and less to the benefit of the environmental ecosystem. Furthermore, Aragon-Correa and Sharma (2003) pointed out that the resource-based view of incorporating environmentally proactive corporate strategies within the more general business environment is likely to enhance a firm's performance and competitive properties but is significantly hindered by many uncertainties. Aragon-Correa and Rubio-Lopez (2007) reveal that although many organisations adopt a pro-active stance towards sustainability issues, as evidenced by their ISO 14000 certifications, myths still need to be addressed within their environmental strategies and are thus rendered unreliable.

Such highlighted lack of confidence in the ability of social-economic (macro) policy to address environmental issues coupled with the inability of (micro) corporate environmental strategies to implement practical solutions to the environmental pressures might indicate further suffering for ecological systems. However, this is not reasonable grounds for dismissing the organisational ability to develop adequate solutions to conflicting ideas. There is reason to be optimistic. Bransan and Gao (2006) reviewed organisational and environmental (O&E) research, and their findings indicate that the most influential management journals were rather more (peculiarly) receptive towards environmental research than corporate, yet their remarks conclusively hint at the need for higher quality O&E research in general management journals. Therefore, this study aims to contribute to further understanding of this presumed conflict of interests and bring new information from the field by approaching the debate regarding “Who Sustains Whose Sustainability” (Banerjee, 2003).

In a call for papers encompassing the links between accounting, finance, and managerial theory toward corporate sustainability performance, Ball (1997) discusses an “enabling accounting agenda” in which accounting as a craft can go beyond its commonly perceived role of simply reporting on financial figures alone, but towards providing an “emancipatory” solution to the issue of environmental sustainability. Broadbent et al. (1997, p.273) bring forth the perception that accounting 'can be a subjective communication for emancipation which can go beyond conventional accounting and measurement of the supposedly objective.' Indeed, a key challenge is presented in the concluding remarks: If accounting were to play an enabling role in easing the social-environmental and economic tensions, how would we know a change when we see it? Thus, the motivation for this study is that accounting holds such a vital role by being informative and, as such, can indicate the progress at which organisations are implementing change and bringing about solutions to the deteriorating environment and related concerns.

From a traditional economic viewpoint, firm productivity is likely to be detrimentally affected if the producers are now required to divert their scarce resources toward

eliminating or reducing harmful emissions to the environment instead of typically producing valuable market goods alone. Using traditional methods of measuring growth (with the total factor of productivity), Christiansen and Haveman (1981), Gollop and Roberts (1983), and Jaffe et al. (1995) seem to echo the concerns of early arguments in this regard and find warranted empirical evidence. Walley and Whitehead (1994) found that increased environmental regulation led to unproductive investments, higher costs, and possible loss of competitive advantage.

However, some advocates have come to challenge this view. Repetto et al. (1997) empirically discovered a positive relationship between firm productivity and environmental regulation, stressing that the traditional methods of measuring productivity failed to account for improvements in the environmental performance of organisations. Additionally, Kjetil and Larsson (2007), writing under the topic "Do environmental regulations hamper productivity growth?" contrasted the Malmquist productivity index in its traditional form and an adjusted "Environmental Malmquist productivity index" which accounted for environmental performance. Their findings support the growing critique of the failure of conventional methods in economics to account for the improvement in environmental performance. Thus, they rejected the traditional factor of production methods as being biased towards economic benefit. It may be a solid premise for investigating firm efficiency under environmental regulation using other methods encompassing an environmental scope. Newer accounting methods may better explain solutions to easing the economic-environmental standoff.

Furthermore, in what has come to be known as the "Porter Hypothesis", Porter (1991) put forth his idea of a 'win-win' situation in the event of environmental regulation imposed on organisations. Porter and Linde (1995) expanded the arguments for the hypothesis by claiming that the said environmental regulation brought new information to firms, resulting in opportunities, for instance, removing inefficiencies and identifying strong potential for innovation and technological adoption. This idea considers that the environment and competitiveness are compatible when adequately designed

environmental regulations stimulate innovation, leading to a competitive advantage for the firm. Indeed, studies support 'early mover' competitive advantages to firms that initiate proactive environmental strategies (Dean & Brown, 1995; Nehrt, 1998).

Other studies have focused on how firms with a pattern of environmental practices that went beyond compliance with environmental regulations were found to be associated with improved financial performance (Klassen & McLaughlin, 1996; Judge & Douglas, 1998). Khan et al. (2021) found mixed results using financial indicators to compare green innovation practices to firm financial performance. They reported a positive relationship between green innovation and returns on equity (ROE) and returns on investment (ROI). However, a contrary relationship existed with returns on assets (ROA). There has been an acknowledgement that firms need to create value in adopting a shift towards sustainability, implying firm-level competitiveness, similar to Porter's win-win situation for innovators within a specific industry. Hermundsdottir and Aspelund (2022) examined how sustainable development strategies affected firm performance through value creation, cost reduction, and risk reduction and found a positive relationship between environmental strategies and all the performance variables.

Although significant debate has been thrust into the relevance of Porter's theory, there appears to be no unified stance when empirical evidence is considered. For instance, while Albrecht (1998), Murty and Kumar (2001), and Shunsuke (2004) find supporting evidence, Marklund (2004), on the other hand, does not find any significant result. Broberg et al. (2013) found no supporting evidence and concluded that harsh regulation led to efficiency loss. There may be a need to re-examine the 'win-win' issue using an appropriate method that does account for environmental performance under regulations hand in hand with economic efficiency.

Numerous methods of testing a firm's production output efficiency encompassing environmental concerns have been attempted before. Regarding energy and environment studies, Zhang and Choi (2014) reported that distance functions enjoyed

extensive application. Advantageous because they do not require specific cost or price information but rather quantifiable material from the input and output processes; two primary variants have been used. First is the 'Shephard distance function,' as applied by Coggins and Swinton (1996), Hetemäki (1996), Swinton (1998), and Marklund (1999). However, this method underestimates a firm's attempts towards regulation compliance by assuming the simultaneous increase in production of both desirable and undesirable products (such as emissions); this inflexibility disregards the reduction of the 'bad'. In remarkable contrast, however, the 'Directional distance function' assumes a simultaneous increase in the production of both the desirable products and a decrease in the 'bad' goods; it is flexible in recognising environmental performance within the general firm performance. This method has been adopted to test the Porter hypothesis, which states that organisations can be more efficient under tight environmental regulations (Färe et al., 2002; Marklund, 2005). By assuming a positive correlation between firm efficiency and environmental regulation, the hypothesis has been tested by regression analysis of the results of the former against a proxy for the latter.

Several studies investigate the effect of regulation on efficiency but do not necessarily test the Porter hypothesis. Boyd and McLeland (1999) and Hernández-Sacho et al. (2000) applied hyperbolic efficiency measures that assumed producer efficiency resulting from a simultaneous expansion in both desirable output and a decrease in undesirable output. However, the departure in their analysis on the regulatory intensity arises from their assumption that the regulatory impact either did not or did affect producing firms through efficiency loss. It could be deduced that their approach lacks any positive correlation between output efficiency and regulation. Additionally, Hernández-Sacho et al. (2005) also assumed an increase in the production of desirable output with respect to less input and simultaneous zero change in the level of undesirable output. Therefore, these methods do not at all relate to the Porter hypothesis.

1.2 Purpose and Structure of the Study.

This study will measure the effect of environmental regulation on firm efficiency by modelling firm efficiency as a composite of economic efficiency and improved environmental ambience, a desirable win-win situation.

Testing the Porter hypothesis focuses on the organisation's technical production process. Following Färe et al. (2002) and Marklund's (2005) methodology, the directional output distance function shall be applied to represent the production technology. The method assumes dual expansion in productivity of goods (or 'good outputs') as well as contraction of emissions (or 'bad outputs'). It leads to the hypothesis below.

H: Production output efficiency is positively related to environmental regulatory intensity.

A higher intensity of regulation should result in more efficient production of desirable goods and reduction of undesirable goods. By applying a regression analysis of the technical output efficiency results against a proxy for regulatory intensity, Porter's theory is once again put to the test. Furthermore, by avoiding any restricting assumptions about the results of the regulation on efficiency, the procedure renders itself valid for testing for an empirical relationship.

This study contains a theoretical presentation of the issues regarding production efficiency and environmental regulations and insight into the hypothesis and past approaches. The latter comprises an empirical section covering the methods, data, testing, and conclusion. Chapter 1 introduces the background to the topical area and highlights the problem. The rest of this paper follows this structure: Chapter 2 presents the literature review. The methodology used in the study is described in section 3. While Section 4 deals with the data applied in the study, Section 5 discusses the study's empirical results. Finally, section 6 summarises and concludes.

2 Literature Review

This section will focus on the most enlightening discussion on the aspects of the sustainability paradigm represented by environmental policy regulations and how this affects the firm performance. Porter's hypothesis and its implications as a solution are widely explored.

2.1 Environmental Regulations and Production Efficiency.

The economic environment in which firms operate has always been characterized by several rules and regulations representing government policies. Their intention may be to control goods and services, maintain standards, work safety, or prevent damaging corporate behavior. Ultimately, regulated firms must comply with these regulations, and thus, they are restricted from acting in a certain way. Several commentators have debated the effects of environmental regulation on the economy. Most notable is the opposition to environmental regulations by many modernists due to their view that environmental regulation was a burden to economic growth (Gray, 1987; Barbera and McConnell, 1990; Gray and Shadbegian, 1993).

However, some postmodernist ideas have come to challenge this seemingly outdated perception. Magat (1979) and Stewart (1981) suggested that the presumed conflict between economic development and environmental preservation was false and even stated that new investments were suitable for environmental quality due to continuous innovation in products and processes. Other researchers soon voiced the possibility of environmental regulation to promote technological innovation (Ashford and Heaton, 1983; Ashford et al., 1985; Porter, 1991; Porter and Linde, 1995), a typical postmodernist belief in innovative solutions to environmental concerns. The definition of technological innovation, according to Ashford et al. (1985), is the first commercial application of a new technical idea. Additionally, some technological responses to changes in regulation

include adopting compliance technology, change in process technology, product substitution, and, in exceptional situations when the desired technology is lacking, could stimulate research and development. Consequently, technological innovation arises from the basis that the regulatory strategy's environmental goals can be optimised hand in hand with economic growth or benefit to the firm. Thus, it is necessary to have a properly designed regulatory policy that captures the essential perspectives of stringency, flexibility, and timeframe for innovative solutions rather than focusing on which economic mechanisms are better for innovation (Klemmer et al., 1999).

In recent years, a great deal of attention has been focused on the role of productivity in enhancing global economies. As part of an economic barometer, the rising trend in productivity has been documented in the United States and has since captured a great deal of attention (Palia and Lichtenberg, 1999)¹. Indeed, productive efficiency is closely associated with firm value and is widely used in empirical research. For example, Studies try to link productivity with firm value using variables such as labour (Baily and Schultz, 1990) and ownership characteristics such as managerial (Hubbard and Palia, 1995) and institutional (Lang et al., 1989 and Servaes, 1991) and family (Martikainen et al., 2006). Thus, studying production approaches at the micro or firm level is crucial. This study aims to contribute to the empirical modelling of productivity concerning regulated firms.

2.2 The Porter Hypothesis.

Porter (1991) first proposed the theory that environmental regulations benefitted corporations by making firms aware of hidden costs associated with pollution and, thus, the likelihood of taking beneficial measures and attaining competitive advantages. Porter and Linde (1995) further expanded the arguments for the theory by suggesting

¹ Evidence in this case shows that an approximately 90% increase in real per capita in the United States is credited to efficiency growth.

that adequately designed environmental regulations, when pursued correctly, would appear to firms as a free, if not a “paid lunch”. They likened the situation to “lots of 10-dollar bills lying on the ground waiting to be picked up. Further, they brushed off criticisms from mainstream environmental economics as being of a “static mindset” that ignored innovation. Thus, the theory seems to revolve around regulation, forcing firms to “overcome organisational inertia and foster creative thinking” and thereby increase profits.

The illustration in Figure 1 below shows an interpretation of Porter's theory and how regulations induce firm innovation and lead to efficiency.

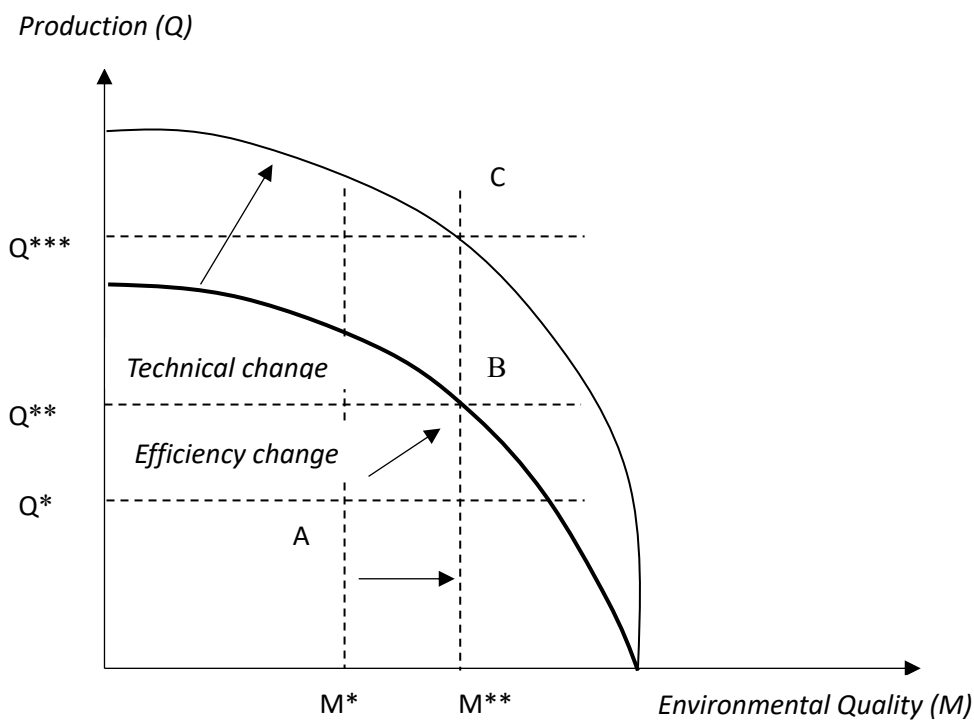


Figure 1. The Porter Hypothesis (adapted from Marklund, 2005).

Given an economic output possibility frontier represented by the bold curve, when the current environmental policy is set at M^* , the production frontier is confined to the area

to its left but within the bold curve. According to Porter (1991), firms cannot be aware of existing opportunities due to a lenient environmental policy. This aspect is represented by a company operating at point A producing Q^* capacity of commodities. At level A, the firm can increase production without using further inputs at the expense of the quality of the environmental ambience. It could be implied that firms here operate with technical inefficiency because they have yet to maximise their potential, located right at the bold production frontier.

A situation may arise when the government or other institution introduces tighter environmental regulation, implying that the policy tightens from M^* to M^{**} . Porter's theory suggests that firms reflect upon their strengths and weaknesses and realise incentives for improvement through innovation. From the figure above, this realisation is indicated by the movement from point A to B. Firm operation at point B represents higher productivity than point A, meaning that more goods are produced, as shown by the movement from Q^* to Q^{**} . The cost of stricter regulatory compliance may be significantly reduced through adaptation to more environmentally friendly technology, which delivers better product and process innovation. Such innovation is represented by the outward shift of the product possibility frontier, as shown by the thinner curve. With the new technological innovation, the higher marginal productivity ensures that with limited resources, it is now possible for the firm to produce more goods and services without compromising the environmental ambience requirement set by the regulation. However, the alternative is also possible. Thus, innovations enable firms to shift their production from B to C on the new thinner curve. To compute the entire effect of the new environmental requirement on production, we derive it from the sum of the efficiency gain (Q^* to Q^{**}) and the gain from technological innovation (Q^{**} to Q^{**}).

2.3 Theoretical Debate.

There have been significant objections to the Porter hypothesis by economists, some of whom think it lacks a theoretical foundation. Many have questioned why regulation would be necessary initially to stimulate producers to take their beneficial measures. Palmer et al. (1995) raise doubt by asking why companies would not take their beneficiary measures toward efficiency, as claimed, without the need for government intervention (in the form of regulation). They pointed out that the lack of voluntary action by firms that have the option of making environmentally friendly products and services means that such investments are not deemed profitable and, therefore, external to the business interest. Porter and Linde (1995) offered some reasons why government intervention is necessary: to signal to firms their resource inefficiencies and potential technological improvements, disclosure requirements would increase information processing and enhance decision-making, reduce uncertainty about environmental investments, to pressure firms to innovate, levelling the playing field, and to serve as an indicator of a futuristic tougher stance towards environmental regulation so that long-term marginal cost of compliance falls as the stringency of regulation increases.

Organisations' rationality is in the hands of their managers, and sometimes, they pursue goals that are divergent from profit maximisation. Some managers may be risk or cost averse (Aghion et al., 1997) and, in the process, miss real opportunities for good, profitable investments. Managers' values may not represent the firm values when short-sighted interests make them blind to present costly but long-term profitable investments (Ambec & Barla, 2006). Regulation is, therefore, a panacea to this behavioural problem by requiring managers to prioritise the adoption of innovative solutions which benefit the firm. Similarly, Ambec & Barla (2002) discussed how a regulatory framework caused organisations to overcome sluggishness to innovate. They considered managers who held onto private information regarding the actual cost of beneficial innovation, using it much like extracting rent from the organisation. The effect of environmental regulation

would be to lower this rent, and the firm can be profitable by offsetting this cost and fostering technological innovation.

Another issue of contention of Porter & Linde (1995) about "free lunches" or "low-hanging fruits" is whether innovation always leads to benefits surpassing the cost of regulation. Diedrich (2002) writes about firm technological preconditions necessary for a cost-minimization choice of technique given allocated emission targets and presents the case for a price-quantity equilibrium analysis as a guide in determining what he terms the "shadow price of undesirable commodities" (or pollution). Its application may be in the form of market prices of tradable permits or emission taxes. Marklund (2005) argues that the implication of "free lunches" would divert attention from the cost-benefit analysis of environmental strategies (by comparing the beneficial effects of regulation to the costs of implementing them). The choice of technique is essential because its adoption is often necessary in the long run; cost-benefit analysis remains essential for any successful environmental strategy.

Regarding the above-mentioned tradable permits, specific regulations create "scarcity rents" that could benefit firms. Mohr and Saha (2008) linked scarcity rents to the Porter hypothesis by showing that firms could benefit by redistributing these costs onto their customers, thereby earning profits. In the first tier, the European Union Emissions Trading Scheme, for example, Newell et al. (2013) showed how regulated energy generation plants passed onto their customers the opportunity cost (scarcity rents) of the carbon allowances they received freely from the regulator. However, there was some discussion that this market-based initiative had some imperfections that allowed for price manipulation, as evidenced by price fluctuations (Hinterman, 2011). However, Andre (2015) suggested that scarcity rents resulting from strict environmental regulations were so flexible that regulated firms could benefit, but neither with the need for innovation nor domestic comparative advantages.

Additionally, Jaffe and Palmer (1997) believed that the Porter hypothesis still needed clarification due to its ambiguity or need for a properly defined scope. They classified the Porter hypothesis into three subdivisions. First is the "weak" version, in which they theorised that environmental regulation would stimulate certain environmental innovation. Secondly, the "narrow" version is one in which a flexible policy would give firms greater incentive to innovate than merely prescriptive regulation. Lastly, the "strong" version asserts that properly designed regulation would induce cost-saving innovation that compensates for the cost of regulation compliance. Indeed, Ambec et al. (2006) tested the significance of these variants of the Porter Hypothesis, and they reported strong support for the "weak" version and limited support for the "narrow" and "strong".

Leeuwen and Mohnen (2017) also implied that most Porter hypothesis tests fell into the single-equation or the reduced-form model. However, they found significant support for the weak version and slight support for the strong version of the Porter hypothesis. Similarly, Lanoie et al. (2008) tested three variants of the Porter hypothesis. First, based solely on a proxy of regulation; second, by subgrouping firms according to pollution intensity and based on firm exposure to international competition. The latter are all aspects that Porter mentions in his theory. The findings confirmed Porter's hypothesis, especially for firms operating in a dynamic environment of competition. However, the opposite was observed for intense-polluting industries that experienced long-term loss of productivity. This might indicate that firm external competition is a more important factor in firm efficiency gains than the intensity of regulation. Perhaps the regulations are poorly designed or better suited when market-based (Ambec et al., 2013). Kreichel and Zeisemer (2009) claim that the definition of the 'weak version' of the Porter hypothesis differed by various researchers due to their different approaches to factors of productivity, profitability, competitiveness, production efficiency, or simply in environmental products. These nuances would likely indicate the conditions upon which the Porter hypothesis would be valid rather than outright agree or dismiss it.

On the other hand, many studies find partial empirical support for the Porter hypothesis. In the following theoretical discussion, the papers acknowledge that newer capital is more productive and less polluting than the old, therefore hinting at technological change as a basis for the Porter theory. Under a taxation policy, Xapapadeas and Zeeuw (1999) show that the external shock from an emission tax per unit of emission motivates companies to seek out new technology, which is cheaper in the long run due to its lower pollution properties. However, they do not find evidence of a 'win-win' situation, that is, a simultaneous increase in company profits and improvement in environmental quality. Instead, there appears to be a "bittersweet" situation in which new investments in the new technology reduce the overall capital stock (or down-sizing effect). At the same time, the capital's average age is reduced, increasing its average productivity (referred to as the modernisation effect).

Mohr (2002) demonstrates with the learning-by-doing model how newer technology could benefit both environmental quality and firm productivity. He argues that all firms operating in an industry are assumed to be efficient under that same technology, reaping economies of scale. However, one firm attempting to adapt to newer technology may lose economies of scale due to the workforce's unfamiliarity with the new technology, hence short-run costs and loss of competitiveness. The case might be different if the government policy on the environment required all the companies in the industry to adapt the technology so that the environmental ambience is improved and, at the same time, the workforce in the entire industry, in the long run, gets experience with the technology. As mentioned earlier (Ambec et al., 2013), this would imply a well-designed regulation that levels the playfield.

On the other hand, Feichtinger et al. (2005) suggested that despite learning and technological progress, certain conditions undermined the position held by Xapapadeas and Zeeuw (1999). They found that a strict progressive environmental policy negatively impacted industry profits.

Under the umbrella of game theory, studies by Ambec and Barla (2002) considering a divisional manager or shareholder whose goal is to maximize private utility and a social welfare maximizing regulator that grants the maximum allowed emissions reveal that under certain circumstances, the Porter theory will be valid. Their findings show that regulation positively impacts investments in Research and Development due to the increase in the marginal benefit of the investment. The condition upon which Porter's theory is valid would arise from the probability that R&D activities will result in cleaner technology, simultaneously bringing about a high marginal productivity benefit. Popp (2005), however, presented a more cautious approach toward R&D projects and the Porter hypothesis. Due to the uncertain outcome of these projects, a lenient regulation may result in a reluctance to engage in R&D projects. At the same time, a stricter stance would force them to see the profitability of undertaking such projects.

Using a timing-of-adoption model to investigate the Porter hypothesis, Kreichel and Zieseimer (2009) employed a precommitment (anti-Porter) and preemptive (pro-Porter) game in which regulated domestic firms were compared to their foreign unregulated competitors. While domestic firms adopted innovation earlier if the environmental taxation was higher, foreign firms remained sluggish due to the absence of such taxation in their jurisdiction, which was held undesirable due to its erasure of profitability. Their findings indicated that environmental taxation led to a profit drop in the precommitment scenario. However, it also turned a preemptive game into a high-profit one, like in the precommitment game.

Simpson and Bradford (1996) stated that the government would likely provide a strategic advantage to its home industry by introducing environmental legislation. Andre (2015) asserted that Porter's hypothesis was studied domestically and with foreign competition. International competition raises comparative issues of regulation, market share, product differentiation and profitability. By use of a vertical product-differentiation model, Rothfels (2002) investigated a market leader-follower position that resulted from the environmental quality of products made between domestic and

foreign firms in what she termed “leapfrogging.” She found that after the introduction of an environmental policy upon a quality standard, leapfrogging was induced under certain conditions such as cost-advantage or the application of adequate subsidization. The implication was that properly designed regulation would improve the competitive position of domestic firms, resulting in a win-win situation. Similar work by Andre et al. (2009) supported the Porter hypothesis in a game of strategy linking the adoption of green products and the resulting pay-off in profitability. Constantatos and Hermann (2011), on the other hand, applied Cournot’s duopoly model in a market sluggish to adopt green products due to undesirable direct effects (increased costs) and strategic effects (short-term loss of market share). They concluded that regulation forced firms to overcome the inertia and that adopting increased long-term market share and profitability.

The above discussions attempt to show how innovation provides a way to compensate for changes in legislation, which could affect the performance properties of competitive forces. However, the assumption of perfect competition, in other words, perfect information flow between all competitors in an industry, is, according to Porter and Linde (1995), far from true. Inefficiencies occur between any two organisations, they assert, as is the information available to them at any given instance, resources, and managerial capabilities. Ambec & Barla (2005) point out that for the Porter Hypothesis to be relevant, there must be at least a single market imperfection, such as spillovers in knowledge (Jaffe et al., 1995), learning-by-doing model of Mohr (2002) or the market power (Simpson & Bradford, 1996). Alternatively, systematic organisational failures within the firm, such as contractual incompleteness, information asymmetry (Ambec & Barla, 2002), and management agency problems, constantly haunt firms. Such inefficiencies are likely to create relativity in performance variables such as competitiveness. Thus, in the presence of intra-firm technical inefficiency, Porter's theory is likely valid, and the implication for all firms is to strive for higher efficiency constantly. As illustrated in Figure 1 earlier, firms operating at point A are thus induced

by regulations to realise greater efficiency and relocate to the production possibility frontier (at point B.)

2.4 The Directional Output Distance Function.

The directional output distance function method was adopted by Färe et al. (2006) and used by Marklund (2005). It is a form of mathematical technique falling under Data Envelopment Analysis, a multidimensional tool for problem-solving; it captures efficiency changes over time, and in this case, it constructs the best practice frontier (Cooper et al., 2007). Firstly, the output production model is defined by stating the output possibility sets and setting boundaries that enable the modelling of both the desirable good outputs and undesirable pollutants. By taking vectors Y , B , and X to represent good outputs, bad outputs, and the inputs, respectively, below is a representation of these vectors.

$$Y = (y_1 \dots y_L) \acute{K}L, B = (b_1 \dots b_M) \acute{K}M \text{ and } X = (x_1 \dots x_N) \acute{K}N, \quad (1)$$

Each set for the year \acute{K} has quantities of variables from a minimum of 1 to the bounded limit of L for good outputs, M for bad outputs, and N for the inputs.

The technology will take the form of the output set $P(X)$ below, which denotes all technically feasible input-output vectors.

$$P(X) = \{(Y, B) ; X \text{ produces } (Y, B)\}, \quad (2)$$

Its shape is assumed to be convex and compact; that is, it converges at $P(0) = \{0, 0\}$ (as later illustrated in Figure 2).

Some assumptions taken include "free disposability" of inputs, that is,

$$\text{if } X' \geq X, \text{ then } P(X') = P(X), \quad (3)$$

It implies that when inputs (X) are changed (X') but not reduced, the new output set contains the original set $P(X)$, or without an increase in inputs, the new output set $P(X')$ is unchanged.

Additionally, producing good and bad outputs (within the technology) is said to be "weakly disposable," as expressed in the equation below.

$$(Y, B) \in P(X) \text{ and } 0 \leq \theta \leq 1, \text{ then } (\theta Y, \theta B) \in P(X), \quad (4)$$

Given a fixed input vector, reducing output can be achieved by proportionately reducing the production of all other outputs, both bad (θB) and good (θY).

Therefore, it appears costly to reduce bad outputs since attempting so would be at the expense of potential revenue from desirable goods.

The idea that desirable outputs are themselves "freely disposable," as expressed below, further complements the weak disposability of bad outputs.

$$(Y, B) \in P(X), \text{ for } Y' \leq Y, (Y', B) \in P(X), \quad (5)$$

Considering a fixed input vector $P(X)$, a desirable output can always be reduced ($Y' \leq Y$) without reducing the other bad output (B). In other words, a targeted reduction in the level of good output could be produced at the same level of bad output as before the reduction in the former.

Therefore, assumptions (4) and (5) above distinguish a bad output as weakly disposable and a good input as freely disposable. It would imply that attempts to reduce bad

outputs always come at the expense of good outputs. However, reducing desirable outputs may not always result in a simultaneous reduction in undesirable outputs.

Another additional assumption is that desirable outputs are said to be “null-joint” with the undesirable outputs, as expressed in equation 6 below.

$$(Y, B) \in P(X) \text{ and if } B=0, \text{ then } Y=0 \quad (6)$$

In order to produce some good output (Y), some bad output (B) must also be produced. Alternatively, if no bad output is produced, then neither is good output produced.

Therefore, the directional distance function becomes representative of the technology function $P(X)$ of the output possibility sets, which can be written as:

$$D_f(X, Y, B; G) = \text{Max}_{\beta'} \{ \beta' : (y + \beta' \cdot g_y, b - \beta' \cdot g_b) \in P(X) \} \quad (7)$$

Whereby ' β' ' is the maximum expansion in both good and bad outputs, respectively, and G is the directional vector of the output $(g_y, -g_b) > 0$ for desirable (y) and undesirable (b) outputs, respectively.

The function above shows the maximum feasible expansion of good outputs and contraction of bad outputs with the technology $P(X)$. Therefore, the vector reaches the output scale at $(y + \beta' \cdot g_y, b - \beta' \cdot g_b) \in P(X)$ when β' reaches the distance function (which represents the technology function) $D_f(X, Y, B; G)$. This property of the directional distance function is well illustrated in Figure 2 below.

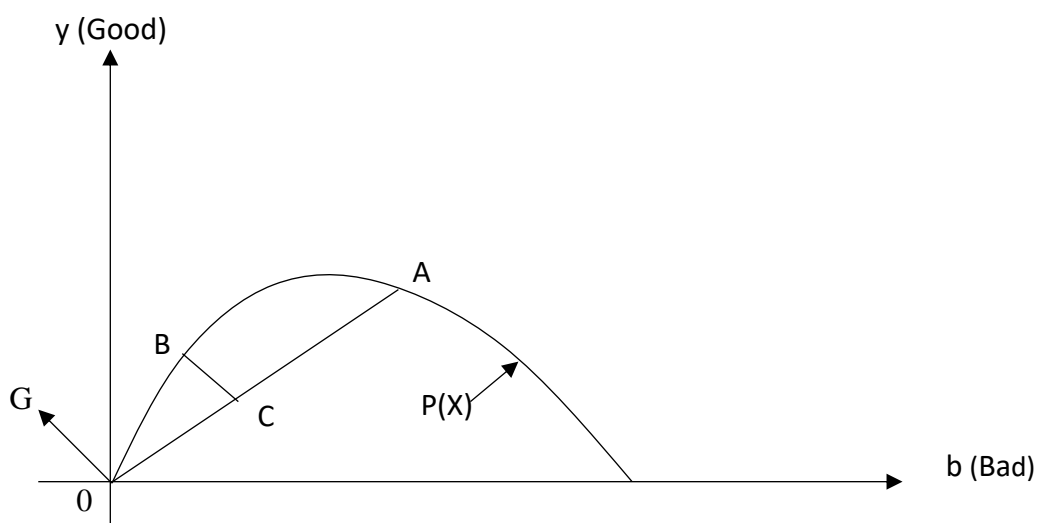


Figure 2. The “G” Directional Distance Function (Chung et al., 1997).

The figure above illustrates the departure between the Shepherd and the Directional distance functions, discussed earlier in chapter 2 of the literature review. While the Shepherd distance function assumes efficiency through a simultaneous increase in output of both good and bad outputs as shown by the output vector OA , the assumption of the “G” direction, on the other hand, moves that output to the boundary of $P(x)$ from point C to B .

Building upon the assumption of “G” disposability from equation 4 mentioned earlier, it is possible to recover the output set from the directional distance function.

$$(Y, B) \in P(X) \text{ on condition that } D_f(X, Y, B; G) \geq 0. \quad (8)$$

In the above equation, the firm is considered efficient when simultaneously increasing good output and reducing bad output because of the assumption of the “G” direction. The distance function shows a zero value for technically efficient vectors on the $P(X)$ boundary, while positive values represent inefficient output vectors below the boundary. In simple terms, a higher positive value means a greater distance from the efficiency frontier (equal to 0) and, consequently, more inefficiency for larger positive vectors and vice versa. When modelling the directional vector, Chung et al. (1997) approached the estimation of the directional distance function by non-parametric techniques by defining the G vector as $(y, -b)$; a simultaneous increase in good (y) and reduction of bad output (negative b).

Conclusively, the translation property below is satisfied by the directional output distance function below.

$$D_f(X, Y+\alpha g_y, B-\alpha g_b; G) = D_f(X, Y, B; G) - \alpha, \quad (9)$$

Whereby α is a positive scalar, as proved by Chung (1996, p.111).

Consequently, the directional distance function inherits the technology's properties, as already shown in equations (3), (4), (5), and (6) of free disposability of inputs, weak disposability of bad outputs, free disposability of good inputs, and null-joint production of good and bad outputs, respectively.

3 Methodology

This chapter presents the empirical models used in the study.

3.1 The Functional Form of the Distance Function.

The directional distance function can be expressed in a quadratic functional form. Assuming the k th firm, or producer, at a given time t , using X inputs and producing Y good and B bad outputs, respectively, the technology employed can be represented by the distance function form (D_f) below.

$$\begin{aligned}
 D_f^{kt}(X^{kt}, Y^{kt}, B^{kt}; G) = & \alpha_0 + \sum_{n=1}^N \alpha_n X_n^{kt} + \sum_{m=1}^M \beta_m Y_m^{kt} + \sum_{j=1}^J \gamma_j B_j^{kt} \\
 & + (\frac{1}{2}) \sum_{n=1}^N \sum_{n'=1}^{N'} \alpha_{nn'} X_n^{kt} X_{n'}^{kt} + \sum_{n=1}^N \sum_{m=1}^M \delta_{nm} X_n^{kt} Y_m^{kt} + \sum_{n=1}^N \sum_{j=1}^J \eta_{nj} X_n^{kt} B_j^{kt} \\
 & + (\frac{1}{2}) \sum_{m=1}^M \sum_{m'=1}^{M'} \beta_{mm'} Y_m^{kt} Y_{m'}^{kt} + \sum_{m=1}^M \sum_{j=1}^J \mu_{mj} Y_m^{kt} B_j^{kt} \\
 & + (\frac{1}{2}) \sum_{j=1}^J \sum_{j'=1}^{J'} \gamma_{jj'} B_j^{kt} B_{j'}^{kt} + \kappa + \tau
 \end{aligned} \tag{10}$$

Whereby κ and τ are producer and time-specific error terms.

The distance function has been solved using a linear programming technique by Färe et al. (2001, 2004), who referred to the early work of Aigner and Chu (1968). The directional vector $g = (1 \text{ to } M, -1 \text{ to } J)$ is chosen so that the translational property imposed seeks to maximise M desirable products while contracting J bad outputs. The function has been estimated as the slope of the tangent at the point in which the “ G ” directional

assumption illustrated in Figure 2, takes the output bundle (Y, b) to the maximum feasible frontier by maximising desirable output and minimising undesirable output by the factor (β) .

Another way to apply the distance function is establishing the "shadow prices" of bad outputs (or the elasticity of undesirable pollutants compared to desirable outputs). For instance, Liao and Lee (2023) made additional assumptions in their modelling to calculate what they termed "pollution abatement cost", which is understood better as the opportunity cost of regulation. It could also be used as a proxy for the stringency of the regulation. The aim is to determine the good output lost due to the regulation. It would likely be in the cost-benefit analysis, as discussed in Chapter 2.3 about the cost-minimizing choice of technique. The focus is only on desirable output. However, this study's unique approach focuses on the potential for efficiency maximisation, defined as a simultaneous increase in desirable outputs and a decrease in undesirable outputs. Therefore, in the discussion later in chapter 5 of this study, potential missed opportunities are presented based on the directional distance function score.

The output distance function in this study will be solved using computer programming techniques with the open-source "R" statistical analysis software (version 4.3.1 2023 -- "Beagle Scouts"). Upon calculating the technical output efficiency estimates of all the producers in the sample in the respective periods t (1 to T), the distance function is comparable to an inefficiency function because any score that is not equal to zero shows some inefficiency. Therefore, it is helpful for comparison throughout the sample period. The resource-efficient company is precisely situated on the distance function frontier, as earlier modelled by Figure 2 in Chapter 2.4.

3.2 Testing the Hypothesis.

The regression model below is applied to test the Porter hypothesis.

$$ED^{kt} (.) = \varphi + \sum_{j=1}^J \omega_j R_j^{kt} + \rho_k + \psi_t + \varepsilon^{kt} \quad (11)$$

In which $ED^{kt} (.)$ represents the previously calculated technical firm efficiency (from distance function) tally in the sample period t , R_j^{kt} stands for the relative intensity of the environmental regulation imposed by the regulator (or the extent to which the firm is constrained) upon the j th undesirable unit of output, ρ_k , and ψ_t are the producer and time dummy variables respectively. In contrast, ε^{kt} represents the uncorrelated error term on the right-hand side variables.

The constants to be estimated are φ and ω_j . Consequently, the Porter hypothesis can be proven by performing t-tests on ω_j .

As adapted from Gollop and Roberts (1983), the equation below represents the relative intensity of the regulation (R_j^{kt}).

$$R_j^{kt} = [b_j^{DES, kt} - b_j^{MAX, kt}] / b_j^{DES, kt}, \quad (12)$$

Whereby $j = 1, \dots, J$, and $R_j \in (0, 1)$, $b_j^{DES, kt}$ is what the producer would otherwise desire to emit into the atmosphere, while $b_j^{MAX, kt}$ is the regulator's set limit.

The regulatory index (R_j) is bound on two sides and therefore lies somewhere between the limits (0, 1); if the regulatory index is 0, then the regulator permits the firms to emit as many emissions as they would desire into the environment, while an index of 1 means that the regulator demands producers not to emit a single emission in which case producers would prefer to shut down production, since the assumption that production

of desirable commodities is “null-joint” with the production of emissions. Therefore, with these restrictions in force, the regulatory index captures the extent to which producers are constrained to behave accordingly.

The actual emissions of the producers are not applied in the above equation because they have already been captured in the dependable variable of $ED(.)$ in equation 11 by the distance function from which it is derived. In other words, the firm's behaviour, including how much emissions it produces, is partly influenced by the regulations' demands.

4 Data

To calculate the directional distance function discussed in the previous section, data has been gathered from the Finnish pulp and paper industry covering three producers whose data is collected from material balance sheets and annual reports of the companies, some of which are available on the producer websites, and some obtained directly from the companies when contacted. The dataset is limited to three companies because of the (lack of or) availability of information and incompleteness because some companies decided to stop voluntary publication of material balance sheets for the period in the study. Material balance sheets typically contain information regarding the product life cycle, covering all product and labour inputs and the resulting outputs, including regulated or harmful substances, work safety incidents, or other ethical issues that may impact the company's image.

Additionally, emission caps are collected from the European Union Transaction Log website (European Commission, 2023), covering the first and second-tier carbon trading periods from 2005-2007 and 2008-2012, respectively. Gathering relevant data requires meticulous coverage of the entire installations log to attain each producer's total. As mentioned above, the sample eventually trickles down to four years of observation due to the complete availability of information for the required study input and output variables. For each state-allocated producer, carbon limits are set and constitute a producer (k) and year (t) panel. The time scope covers four years, from 2005 to 2008. The pulp and paper industry falls under the European Union Emissions Trading Scheme due to the heat-energy intensity nature of its consumption, as all plants that have installations whose electricity production reaches the threshold of twenty megawatts annually qualify for carbon dioxide emissions regulation. The names of the firms are not published in this study because the producers requested that they not be disclosed. All the plants are involved in producing pulp, which is a desirable output (y). Production requires inputs of labour (x_1), electricity (x_2), wood fibre (x_3), and capital (x_4).

Carbon dioxide is the (regulated) bad output produced (b_1). Descriptive statistics for inputs and outputs are summarised in Table 1 below. However, the original panel data from the sample firms are presented in the Appendix. The yearly data appears for the same firms in consecutive order in all the tables and appendices where appropriate.

Table 1. Descriptive Statistics.

Year	Variable	Mean	Standard Deviation	Minimum	Maximum
2005	Y (tons)	2767.83	417.78	433.50	5693
	b (tons)	2118.40	2155.16	269.42	5166
	X1 (no.)	6433	3767.46	872	17322
	X2 (MWh)	2924	980.05	1343	5891
	X3 (m ³)	1027.67	780.13	594	18860
	X4 (mil)	6297.03	3286.87	1648.70	15541
2006	Y (tons)	3161.39	454.24	502.16	6463
	b (tons)	2447.30	2550.32	290.89	6054
	X1 (no.)	5596	3265.65	865	14946
	X2 (MWh)	3403.10	1185.89	1613	6870.30
	X3 (m ³)	11823.47	904.06	668.41	21700
	X4 (mil)	6068.28	2877.29	1736.50	14469
2007	Y (tons)	3243.67	514.54	501	6714
	b (tons)	2447.03	2539.90	321.10	6069
	X1 (no.)	4857	2822.53	619	13086
	X2 (MWh)	3430.17	1224.12	1618	6973.50
	X3 (m ³)	11709.33	278.36	695	22330
	X4 (mil)	5948.33	2637.71	1674.10	13953
2008	Y (tons)	2972.83	431.22	531	6024.50
	b (tons)	2328.83	2482.06	334.50	5839
	X1 (no.)	4557	2617	574.00	12241
	X2 (MWh)	3071.41	1034.78	1608	5957.22
	X3 (m ³)	11201.33	690.61	750	20676
	X4 (mil)	5967.03	2502.83	1692.60	13781

The firms are not named due to privacy concerns; therefore, for this study's sake, they shall be referred to as k1, k2, and k3 for easy identification and comparison purposes.

The units indicated in parenthesis represent personnel number (no.) for labour, megawatt hours (MWh) for electricity, tons for good and bad outputs (ton), and cubic meters (m³) for wood fibre.

Before running the data through the open-source R version 4.3.1 – ‘Beagle Scouts’ statistical analysis software for the directional distance function, it is necessary to convert the decision-making units presented in Appendix 1 into a "normalised" form by dividing each one by the observed average for each year. Thus, the normalised observations in Table 2 below are more accessible to manipulate with techniques in the statistical analysis software mentioned above (Cooper et al., 2007).

Table 2. Normalised Data.

Year	k	Y	b	X1	X2	X3	X4
2005	k1	0.7865	2.4389	0.1717	0.5259	1.1073	0.2618
	k2	0.1566	0.1272	0.1355	0.4593	0.0577	0.2701
	k3	2.0568 (0.6379)	0.4338 (0.5124)	2.6928 (0.3972)	2.0147 (0.7866)	1.8348 (0.4896)	2.4679 (0.5589)
2006	k1	0.7968	2.4737	0.1747	0.5071	1.1081	0.3294
	k2	0.1588	0.1188	0.1545	0.4739	0.0565	0.2861
	k3	2.0443 (0.6372)	0.4025 (0.4909)	3.0774 (0.4364)	2.0029 (0.7837)	1.8532 (0.4878)	2.4324 (0.6120)
2007	k1	0.7756	2.4501	0.1781	0.4953	1.0336	0.3728
	k2	0.1544	0.1296	0.1274	0.4717	0.0593	0.2861
	k3	2.0698 (0.6282)	0.4202 (0.5110)	2.6944 (0.3940)	2.0329 (0.7802)	1.9070 (0.4890)	2.3457 (0.6267)
2008	k1	0.7949	2.5073	0.1878	0.5235	1.0872	0.4068
	k2	0.1786	0.1436	0.1260	0.5369	0.0670	0.2837
	k3	2.0265 (0.6601)	0.3491 (0.5009)	2.6862 (0.3990)	1.9396 (0.8169)	1.8459 (0.5121)	2.3095 (0.6435)

In the above table, four decimal places are necessary because they improve the accuracy of calculating the distance function compared to two or three decimal points. The mean firm “normalised” data is also indicated in parenthesis for comparison.

Additional data regarding the allocated emissions caps are reported in Table 3 below, and the quantities presented are in tons of carbon dioxide. This data calculates one of the reported variables in the hypothesis, the “intensity of the regulation”, denoted by “ R ” as presented in equation 11 of the methodology and subsequently presented in Table 4. There is no need to compare emission caps due to the belief or assumption that the regulator assigned each producer based on their energy production capacity. The data is presented annually and in the same order for the respective k^{th} producer or firm.

Table 3. Maximum Allocated Carbon Dioxide Emissions.

Year, t	k^{th} firm	Regulation allocated emissions (tons)
2005	k1	437.92
	k2	269.94
	k3	1007.79
2006	k1	437.92
	k2	269.94
	k3	1007.79
2007	k1	437.92
	k2	269.94
	k3	1007.79
2008	k1	454.55
	k2	153.92
	k3	837.93

5 Results and Discussion

The initial findings are reported in Table 4 below. First, two variables necessary for testing the hypothesis are calculated: the directional distance function (or firm efficiency score) based on the mean-normalized input and output data and the regulatory intensity score for each of the three firms in the sample.

Table 4. Preliminary Results.

Year	K th Firm	Df	R
2005	K1	0	0.9278
	K2	0	0.1930
	K3	0	0.0319
2006	K1	0	0.9278
	K2	0	0.1930
	K3	0.007416641	0.0319
2007	K1	0	0.9278
	K2	0.029039972	0.1930
	K3	0	0.0319
2008	K1	0.009155832	0.9251
	K2	0	0.5398
	K3	0	0.1951

The third column, 'Df,' presents each firm's directional distance function result. All distance function scores of zero indicate that the firm is technically efficient and on the technological frontier. A departure from the frontier shows some inefficiency, and the distance function captures this. It can also be a method of capturing inefficiency. According to the above results, each firm had at least one year in which productivity fell short of its production frontier. The mean firm was consistently situated on the frontier, indicating absolute efficiency within the entire sample. That means that in the

four years the firms were observed, they optimally maximised the use of resources except for a single year.

The fourth column, '*R*' of Table 4, represents the regulatory intensity, in other words, the extent to which firms are constrained by regulation, as explained earlier by equation (12) in chapter 3.2 of the methodology. According to the table, the first three years have the same figures for each respective firm, reflecting the first-tier European Union regulatory limits set upon the sample firms; thus, the minimum regulatory intensity is 0.0319, the middle figure is 0.193, and the highest is 0.9278. One way of understanding these values is that the government regulation constrained the respective firms' emission level by 3.19%, 19.3%, and 92.78%, respectively, as minimum, middle, and highest levels, compared to what the firms desired to emit maximally. It is not calculated for the mean firm. Notably, in 2008, the figures changed, reflecting the second-tier European Union regulatory demands, which led to the government setting new emission limits for the firms. While the lowest and middle intensity rose to 19.51% and 53.98%, respectively, the highest intensity barely reduced to 92.51%.

One way of understanding this information is that it could help visualise missed opportunities; for instance, in 2006, firm k3 had a distance function score of 0.0074 away from the frontier. The firm could have efficiently increased its desirable pulp output (*y*) by 0.74% while simultaneously reducing the undesirable output (*b*) of carbon dioxide by the same proportion. The same can be stated for firms k2 and k1, and Table 5 below presents the implication of missed opportunities according to the score of the distance function, which will be further discussed later.

Table 5. Distance Function and Missed Opportunities.

Year	K th firm	Df.	ΔY (tons)	Δb (tons)
2005	k1	0	0	0
	k2	0	0	0
	k3	0	0	0
2006	k1	0	0	0
	k2	0	0	0
	k3	0.007416641	47.83	7.38
2007	k1	0	0	0
	k2	0.029039972	14.53	9.31
	k3	0	0	0
2008	k1	0.009155832	21.58	53.13
	k2	0	0	0
	k3	0	0	0

Column ΔY shows the possible increase in desirable output, and the one marked Δb shows the simultaneous decrease in emissions, reported in tones, a missed opportunity. We can determine the missed opportunity by multiplying the distance function score by the respective good or bad output observed for that year. The first reported inefficiency was in 2006; firm k3 could have realised increased good output by 47.83 tons with a simultaneous reduction of carbon dioxide emissions by 7.3 tons. In 2007, firm k2 would have increased the output of pulp by 14.53 tones with a realised reduction in carbon dioxide by 9.31 tones. In the last observed year, 2008, firm k1 could have optimised its production by increasing the desirable pulp output by 21.5 tons while simultaneously reducing carbon emissions by 53.13 tons. Marklund (2005) has applied this method. It partially supports the Porter hypothesis because firms can realise what they missed and effect changes where necessary to create a win-win situation.

Therefore, the preliminary results of Table 4 provide the necessary data to solve the Porter hypothesis using regression analysis. In turn, the results of the regression of the technical output ED(.) upon the regulatory intensity, R , using programming techniques again in 'R statistical analysis software,' are presented in Table 6 below.

Table 6. The Main Results of Coefficients.

	Estimate	Standard Error	t value	Pr (> t)
Intercept φ	0.005092	0.003886	1.310	0.219
$R \varpi$	-0.003026	0.006832	-0.443	0.667

The above-tabulated results follow a regression test on the null hypothesis that no relationship exists between $ED(.)$ and R , as discussed in equation (12) in chapter 3 above. The intercept value is 0.005092, and the regression or gradient of slope value is -0.003026. It is interesting to note that for the regulatory intensity (denoted by R), the p-value of 0.667 is situated high above the 10% significance level, suggesting that it is not a significant statistical predictor of the relationship; in other words, there is no likelihood of rejecting the null hypothesis. Therefore, this study does not find supporting evidence that tighter environmental regulations improve firm efficiency. Other results, such as R-squared and residuals, are presented in Table 7 below.

Table 7. R-squared and Residuals.

Multiple R-squared	0.01924
Adjusted R-squared	-0.07884
F-statistic (10 degrees of freedom)	0.1962
Residuals:	
Minimum	-0.004995
Median	-0.002871
Maximum	0.024532
Standard Deviation (10 degrees of freedom)	0.008906

The Multiple R-squared suggests that technical firm efficiency could be 1.92% attributed to regulatory intensity, but this does not prove any causal relationship, and the Adjusted R-squared is predictably lower than the Multiple R-squared. The F-test of 0.1962 has a p-value of 0.667; in this case, it is a model with only one predictor value.

Additionally, diagnostic plots to test for the robustness of the linear model were generated as screenshots from the statistical analysis software “R version 4.3.1 – ‘Beagle Scouts’” and are clarified in the next section below.

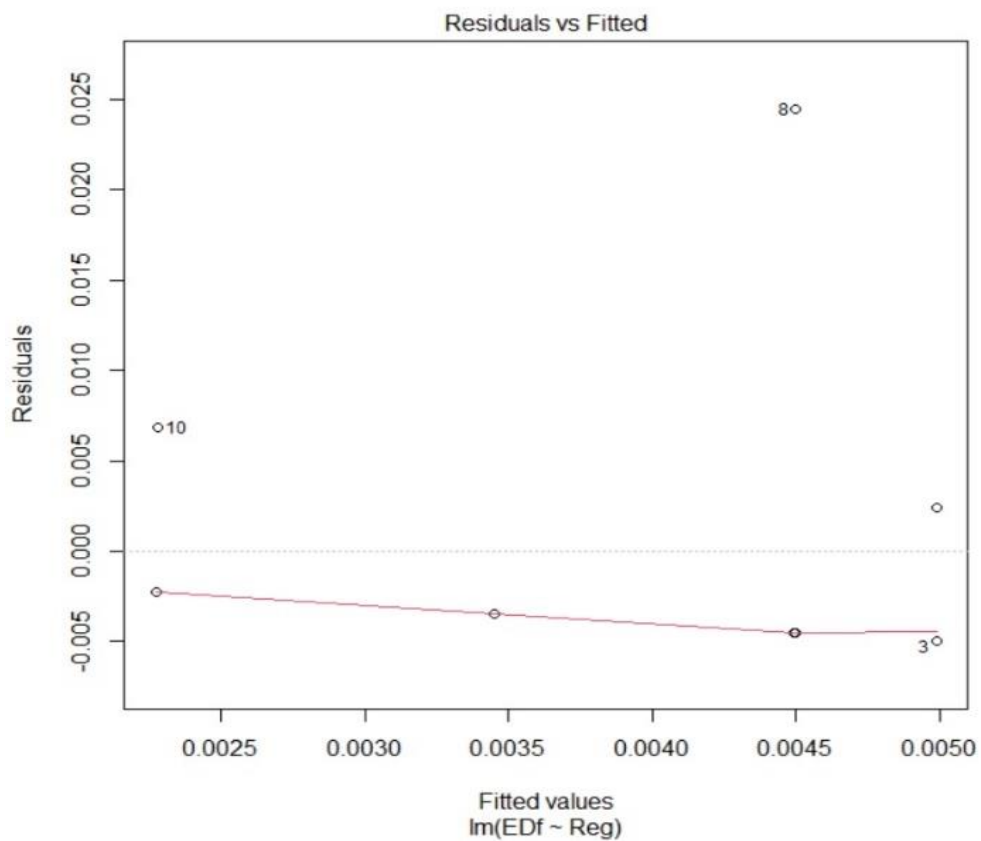


Figure 3. Residuals vs. Fitted residuals.

Figure 3 above presents a more visual account of residuals compared to fitted values. The red line is approximately horizontal or linear, with slight deviation. The linear model is entirely appropriate for this data set.

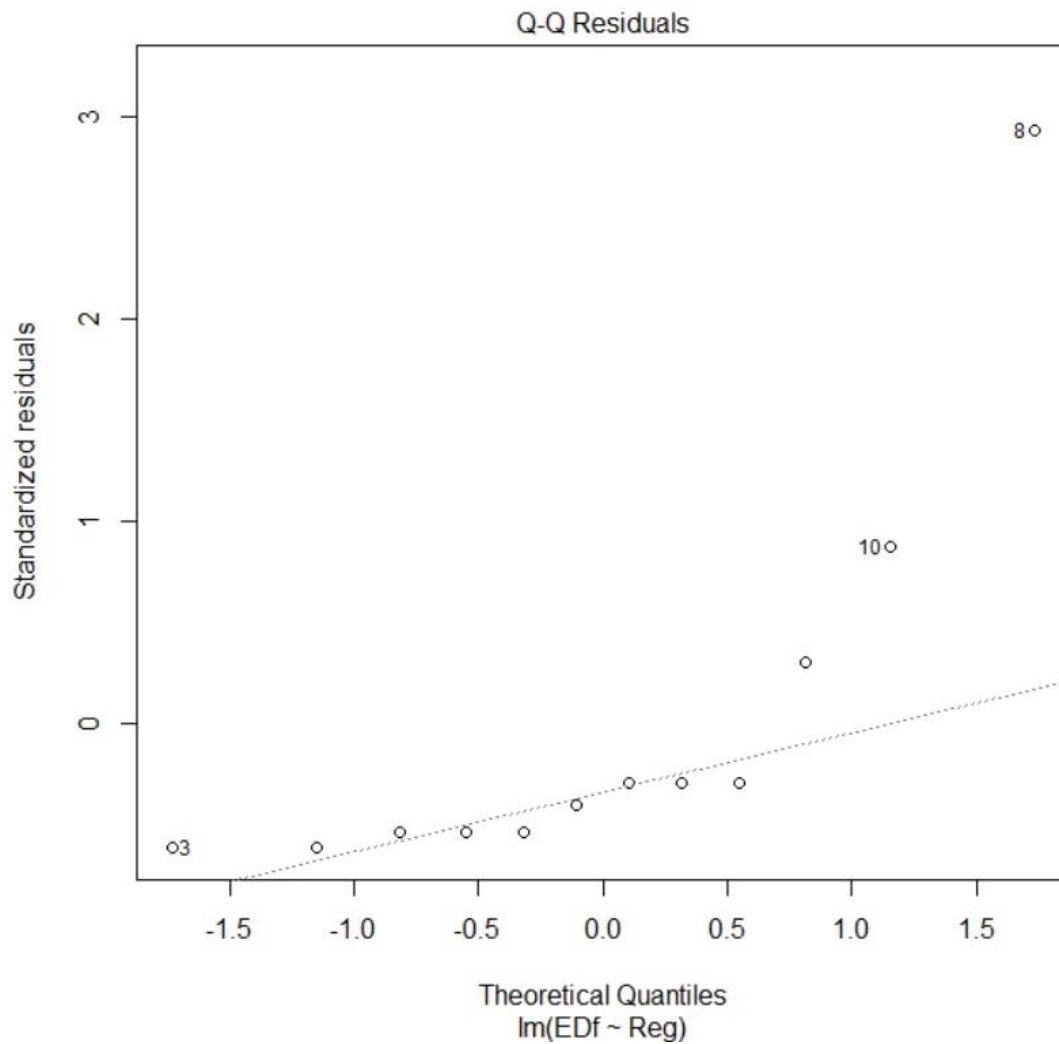


Figure 4. Normal QQ Plot.

In the next robustness test shown by Figure 4 above, the Normal Q-Q graphical plot reveals minimal deviations from the straight diagonal line (under the least squares regression assumption of a normal distribution of errors), with two more significant deviations at the right-side tail end notable by residuals marked 10 and 8, thus confirming a normal distribution. These two points need to be more significant to support non-linearity.

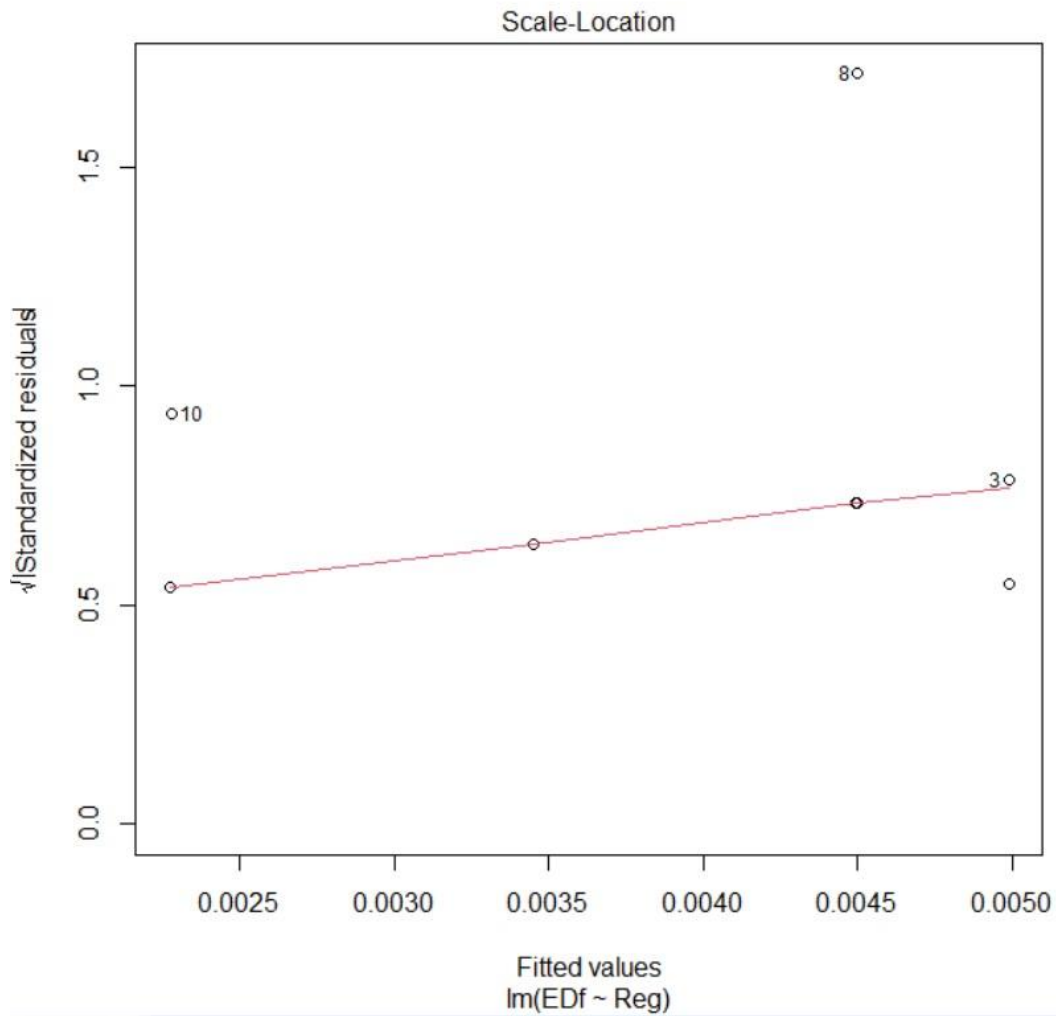


Figure 5. Scale-Location Plot.

The test for unequal variance, or homoscedasticity, is shown in the graph in Figure 5 above. With fitted values on the x-axis and the square root of the absolute residuals on the y-axis, the plotted red line runs horizontally across. Thus, it shows that the residual variance is unaffected by changes in the fitted values, and the assumption of equal variance is likely fulfilled.

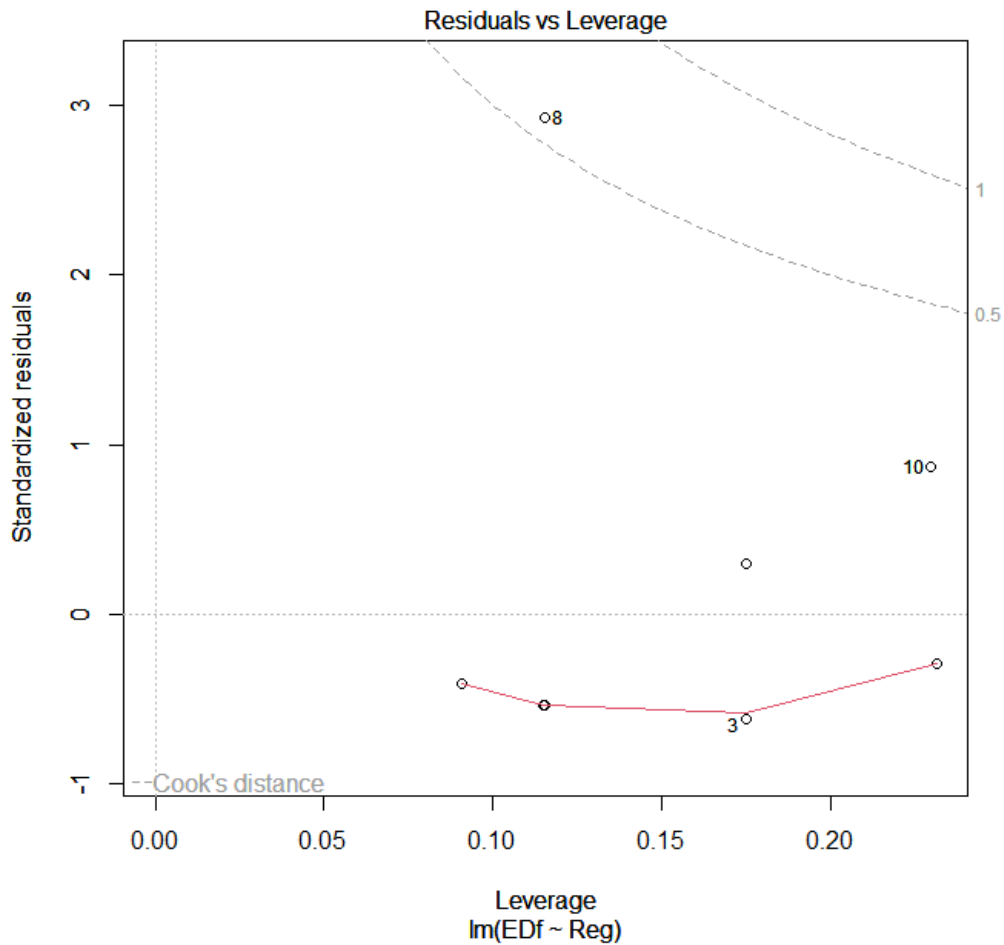


Figure 6. Leverage and Cook's Distance.

'Standardized residual versus leverage' is the last robustness test graphically plotted in Figure 6 above. The residuals are all clustered within a three to minus one deviation from the zero point of symmetry. Firstly, the leverage shows how much the residual values affect the regression. The red line is where the regression line is fitted, and the points furthest and most isolated from the red line have the highest leverage, namely points 8 and 10. However, only point 8 is flagged as an outlier, a residual exceeding Cook's distance threshold of 0.5 and needing further scrutiny. Therefore, another plot is generated below to compare Cook's distance and residual leverage.

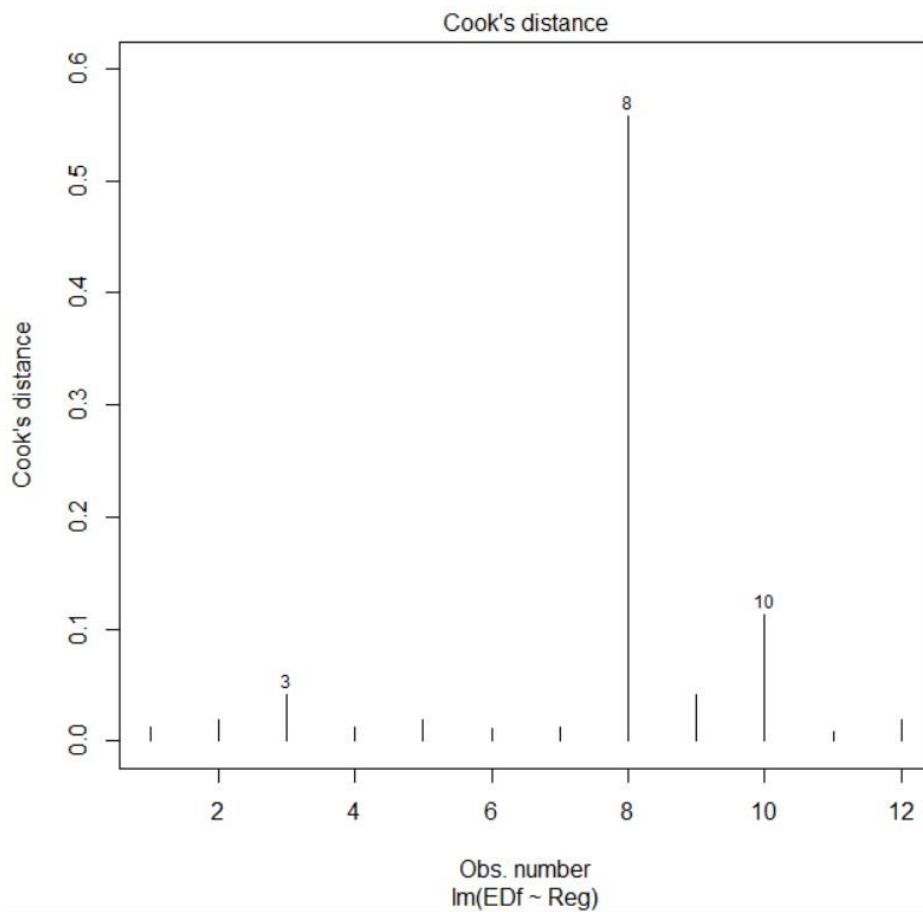


Figure 7. Cook's Distance.

The Cook's distance typically shows the extent to which the elimination of a particular residual affects the regression, a desirable target range usually falling below and to the left the two Cook's distance bands of 0.5 and 1. Figures 6 and 7 imply that removing this high-leverage residual can distort the regression; in other words, residual eight does not follow the general trend of the other residuals. It might indicate a data entry mistake, but after a thorough check of sample data and a re-run of data analysis, the results seem accurate.

Therefore, it can be concluded confidently that the regression model used is linear, with the assumption of a normal distribution and equal variance, and only one outlier residual has the potential to affect the regression.

6 Conclusion

This study aimed to test Porter's hypothesis and the idea that environmental regulations led to a win-win situation for regulated firms by making firms aware of their inefficiencies and, therefore, innovating to be competitive. The theory shows how productive output comprises efficiency and technological changes. Adopting the output distance function provides a platform to measure the productivity change to capture the effects upon regulated firms by defining efficiency as, given inputs and technology, the improvement in quantifiable goods and improved environmental ambience. This method enables not only individual firms to be tested; it could also be used for comparison within a particular industry, nation, or region, such as in the European Union. In this study, the sample was drawn from firms in the Finnish pulp and paper industry. This particular industry is already efficient in energy input compared to other sectors, such as the metal industry. The pulp industry's input process utilises raw timber, recorded in tons, and all the extra discarded bits and parts are re-used in energy generation, which constitutes a renewable fuel source, according to the European Union's renewables policy. Therefore, one input (timber) produces pulp and energy; nothing is wasted. With the assumption that all firms within the industry adopt similar technology, the distance function becomes quite relevant when comparing the efficiency of these firms.

The sample of firms was limited to three because of the need for complete data and mergers, which distorted the data for the period in the industry and led to a drawing down in the number of viable sample firms. Testing of the hypothesis was conducted using regression analysis to verify whether there exists any correlation between the stringency of the environmental regulation and the productive output efficiency of firms. Regulatory stringency was defined as the percentage index of the difference between a firm's maximally desired emission and the legal emission level they must observe.

The results show that for the three sampled firms from the Finnish pulp and paper industry from 2005 to 2008, there was no evidence to support the Porter hypothesis. In other words, there was no proof that environmental regulations made the firms more efficient. However, additional tests showed that only 1.9% of the efficiency realised could be attributed to the same regulatory intensity.

The distance function showed the missed opportunities at producing desirable pulp while reducing undesirable carbon dioxide, a missed win-win situation. Each of the firms was reported to have missed opportunities in at least one year within the study period; although the results were meagre figures, they demonstrate that efficiency differences, however slight, will ultimately set firms apart. The most significant opportunity missed for pulp production was 47.83 tons in 2006, while that of carbon dioxide reduction was 53.13 tons in 2008. However, the method could not pinpoint specific areas or resources requiring improvement.

In conclusion, therefore, this study does not find support for the view that regulation of firms resulted in economic benefit through higher good output productivity, in tandem with improved environmental ambience through carbon dioxide reduction. The distance function, however, provides a platform to understand the effectiveness of the firm's technological innovation and a comparison with other firms within the industry. This simple study sampled a few firms and captured a short period of economic activity; Porter's theory would find relevance in a larger sample and a more extended test period. Additionally, the desirable output modelled was only one good item (pulp) and one undesirable product (carbon dioxide), and yet the model can be fully applied to include multiple desirable and (regulated) undesirable outputs. Proponents of sustainable development and corporate social responsibility who embody a holistic view, that is, all aspects considered together, could model parameters using the directional distance function. Therefore, a richer study has the potential to inform us regarding the relevance of Porter's theory.

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Appendices

Appendix 1. Sample Data.

Table 8. Sample Data Inputs and Outputs.

Year	Firms	Y(tons)	b(tons)	X1(no)	X2(MW)	X3(t.m3)	X4(mil)
2005	<i>k1</i>	2 177	5 166	1 105	1 538	11 382	1 648.70
	<i>k2</i>	433.50	269.42	872	1 343	594	1 701.40
	<i>k3</i>	5 693	919	17 322	5 891	18 860	15 541
2006	<i>k1</i>	2 519	6 054	978	1 726	13 102	1 999.10
	<i>k2</i>	502.16	290.89	865	1 613	668.41	1 736.50
	<i>k3</i>	6 463	997	14 946	6 870.30	21 700	14 469
2007	<i>k1</i>	2 516	6 069	865	1 699	12 103	2 217.90
	<i>k2</i>	501	321.10	619	1 618	695	1 674.10
	<i>k3</i>	6 714	1 041	13 086	6 973.50	22 330	13 953
2008	<i>k1</i>	2 363	5 839	856	1 608	12 178	2 427.50
	<i>k2</i>	531	334.50	574	1 649	750	1 692.60
	<i>k3</i>	6 024.50	813	12 241	5 957.22	20 676	13 781