Environmental Performance and Practice Across Sectors: Methodology and Preliminary Results

Don Goldstein*
Department of Economics, Allegheny College
Meadville, PA 16335, USA
+814-332-3340
dgoldste@allegheny.edu

Rachel Hilliard
Centre for Innovation & Structural Change
NUI Galway, Ireland
+353-91-492932
rachel.hilliard@nuigalway.ie

Valerie Parker
Centre for Innovation & Structural Change
NUI Galway, Ireland
+353-91-495971
valerie.parker@nuigalway.ie

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*Corresponding author.

Abstract: This paper introduces a methodology for measuring and modeling manufacturers' environmental performance and the managerial and technological practices that affect it. Facility level licensing data from the Irish Environmental Protection Agency are used to develop indicators that can be analysed across sectors, addressing the problem that environmental performance and determinants tend to be sector-specific, while modeling and policy interests are often more general. Using Integrated Pollution Control (IPC) information generated EU-wide , this approach should be capable of cross-country extension. The methodology is tested on a sample of Irish facilities in three sectors during 1996-2004. Preliminary results show its usefulness in exploring the determinants of environmental performance at the sector and cross-sector levels, and suggest potential uses in future research.

Keywords: Environmental performance indicators, cleaner technology

1 Introduction

In this paper, facility level data from the Irish Environmental Protection Agency (EPA) are used to develop measures of manufacturers' environmental performance and the practices that might affect it. Ireland was an early adopter of the EU's Integrated Pollution Control (IPC) licensing program. From the mid-1990s through 2004, companies were required to meet IPC's stringent pollution prevention standards and report detailed information on air and water emissions, waste and resource usage, and relevant management and technology practices. (After 2004, IPC was superceded by IPPC, Integrated Pollution Prevention and Control. European Union, 2005) This dramatic shift in regulatory regime provides a natural laboratory in which to study the efficacy of various approaches. To do so, one needs measures of environmental performance and its determinants. We use IPC information generated EU-wide (see Karavanas et al., 2009, for another example) to develop and test a methodology for measuring and modeling these relationships. This approach is thus of special interest because it should be capable of cross-country extension.

The methodology starts from facility level data constructed around sector-based scoring criteria, and creates common measures that connect practices and outcomes across sectors. Our approach thus addresses a recurring problem identified in the literature: environmental performance and its determinants tend to be highly sector-specific, while both modeling requirements and policy interests are often more general (GEMI, 1998; MEPI, 2001; Dewulf and Van Langenhove, 2005).

With respect to environmental performance, we seek a middle ground between indicators that achieve generality by folding all impacts of concern into a single measure (Jaggi and Freedman, 1992; Tyteca, 1999; Fijal, 2007) and those that achieve context-specificity by focusing on individual impacts in single-sector analyses (MEPI, 2001). In this vein, Dewulf and Van Langenhove (2005) create slightly more disaggregated "environmental sustainability indicators," to be used in comparing alternative technologies within a given sector. Also, Karavanas et al. (2008) create facility level indicators that permit comparison with sector peers in either disaggregated or single-indicator performance measures, and comparison of sectors in the latter. They create "sub-indicators" within each of a number of performance "components" (energy use, emissions, etc.) and then choose the highest-impact sub-indicators in aggregating up; we have employed a similar logic in constructing the "key emissions" variable described in section 3. But Karavanas et al. do not attempt to analyze facilities' performance cross-sectorally, a key goal of the present study.

While our methodology for environmental performance follows and extends somewhat this large literature, with respect to environmental practice we have had to break new ground. Dewulf and Van Langenhove's (2005) sustainability indicators are applied to broad sector-level technological alternatives (e.g., photovoltaic solar versus natural gas-fired electricity generation). But there is no research of which we are aware that develops detailed, quantitative representations of companies' technological and organisational actions that might affect environmental performance. The major innovation reported here is to build such representations from the kinds of information generated by EU-wide licensing programmes.

In Sections 3 and 4, we introduce measures for major dimensions of environmental performance and management and technology practices. Section 5 presents some preliminary empirical results in modeling the determinants of environmental performance, exploring the potential of the measurement methodology. There are additional questions that might be investigated using these methods and data, and we discuss several briefly in the concluding section 6. But first, we describe the sources and facilities from which the data are drawn.

2 Data sources and sample

2.1 IPC licensing in Ireland

Ireland's Environmental Protection Agency Act introduced Integrated Pollution Control licensing (IPC) of industry in 1994. Formerly, firms complied with static emission limit values for air and water, set at the time of licensing and not subject to subsequent review. The IPC regulations, in contrast, demanded continuing reduction of environmental impact; a shift of emphasis from pollution treatment to pollution prevention; and regular reporting and site inspection. Beyond meeting performance standards, firms were required to put in place environmental management and information systems and establish environmental management plans that set goals and report on progress The license included the following key components:

Environmental technology: Standards for water and air emissions were set with regard to BATNEEC (best available techniques not entailing excessive cost), requiring all facilities to work towards attaining current BATNEEC. The explicit aim is the development of environmental strategies focused on cleaner technology, rather than 'end of pipe' approaches, making "waste minimisation...a priority objective' (EPA, 1996, p. 1).

Environmental management: Progress toward cleaner production was to be carefully planned, managed, and reported. Licensed firms were required to develop a five-year environmental management programme of projects and to submit an Annual Environmental Report (AER) to the EPA. Included in the AER are details of all environmental projects being carried out, with measurable goals, target dates and results. The Irish EPA has been unusual among EU regulators[1] in its explicit focus on the activity content of structures for environmental planning and management, including 'document control, record-keeping, corrective actions etc.' (EPA, 1997, p. 7).

Facility information available at the EPA includes monitoring results for specific emissions; reports of audit visits by the EPA inspectors; correspondence between the firms and the Agency; and the AERs. These sources provide detailed records of managerial activities, technology projects, and environmental outcomes for the years under license. In addition, separate license application files contain information about technologies and systems in place, providing a snapshot of pre-license period activity and expertise.

[1] A similar approach is taken in the Netherlands (Wätzold et al., 2001).

2.2 Sample selection

We organise our study around three industry sectors. Variations in what companies do that might affect the environment, and how these practices translate into outcomes, are often highly industry sector-specific: technological options, environmental impacts, and supply chain and market demand considerations (MEPI 2001). For generalisability, we sought sectors exhibiting a range of technology, product and market characteristics.[2] The sample starts from all IPC-licensed firms in each sector, defined by NACE categories, beginning with companies sharing four digit NACE codes, but also chosen from the three and even two digit levels when other information suggests a company ought to be included:

Metal fabricating, NACE codes 2811, 2812, 2821, 2822, and 2840. Products include electronics enclosures and cabinets; containers and tanks; structural steel and builders hardware; and radiators and heating panels. Common processes are forging or pressing, cutting, welding, degreasing and cleaning, and coating. Environmental impact-reducing technologies include segregation and recycling of used oils and waste metal, low-VOC or non-solvent cleaning and degreasing, and water-borne, high-solids, or powder coatings. We exclude facilities engaged predominantly in electroplating or casting, because these are very different processes.

[2] Two additional factors facilitated linking the environmental data with financial results for future analysis. First, we favoured industries with a high percentage of single-facility firms, where facility level environmental data would match with company level financial data. Second, we avoided industries subject to substantial transfer pricing bias due to facility 'sales' to same-company subsidiaries elsewhere.

Paint and ink manufacturing, primary NACE code 2430. Products may be solvent or water based. Processes involve mixing of pigments and bases, either manufactured on site or purchased. The key environmental concern is VOC emission; thus water vs solvent based product is a key variable. Manufacturing issues include (non-)enclosure of storage, transfer, and mixing equipment; disposal vs separation and recovery of wash water and/or solvents for equipment cleaning; and handling of waste product.

Wood sawmilling and preservation, NACE codes 2010 and 2030. Processes involve cutting rough wood to shape and size, and pressure treatment for water resistance. Typical products are construction lumber, building frames and roof trusses, posts, and fencing. Toxic pressure treatment substances vs non-toxic alternatives is an important element in environmental performance. We have excluded facilities making composite products such as plywood, fibre board, or veneer products.

The sample consists of 59 facilities with significant amounts of data reported for the variables described below: 21 in metal fabrication, 13 in paint and ink, and 25 in wood preservation and products. The panel of data extends from 1996 (when IPC licensing began for these companies) through 2004 (after which IPC licensing was superseded by IPPC, Integrated Pollution Prevention and Control). It is an unbalanced panel, as not all years (especially early ones) are represented for all variables and firms.

3 Measuring environmental performance

The EPA's licensing approach has been that the performance phenomena that matter, and how they are to be assessed, are highly context-specific. Each facility has its own requirements with respect to what environmental impacts must be monitored, how often, and what limits are permitted. EPA files contain information about licensed facilities' impacts in terms of pollutant emissions, generation and disposition of wastes, and resource usage.[3] For each, we construct common variables that are scored according to the state of the knowledge on sector-specific environmental considerations, but compared across sectors and over time to analyse a wide range of possible relationships. The steps employed for all three impact measures to create this comparability (with exceptions as noted below) include normalisation and within-sector averaging:

Normalising raw data: Measures of facility emissions, waste and resource usage must be normalised by some standard unit of production scale, in order to be meaningfully comparable over time and across firms. Most impact data are in mass units – for example, kg/year. Ideally, these data from facilities in the same sector could be normalised and compared per 'functional unit' of output (MEPI, 2001, p. 29). Because output data is not available for our sample, we normalise mass impacts relative to a proxy, the number of employees (available in financial reports at the Companies Registration Office). Data

[3] The correspondence in EPA files contains indirect data on environmental performance: notifications of regulatory non-compliance involving actual environmental impacts. We also construct a performance indicator based on this, which is omitted in the following to conserve space. Section 6 discusses its use in exploring the relationship between regulatory pressure and environmental practice and performance.

reported in flow units, *e.g*. mg/m^3, are already normalised to the extent that different companies' flow conditions are equivalent. **FN ON EPA OBJECTION TO THIS?**

Within-sector averaging: Once the raw data are normalised, we calculate each annual facility environmental impact value as a ratio with its sector average.[4] When expressed this way, above versus below sector average facilities can be compared across sectors, abstracting from the fact that what might be considered "good" performance is different for each sector.[5]

These comparability steps are applied to three basic sets of environmental performance measures: emissions, waste, and resource usage.

3.1 Key emissions

There are two additional steps in constructing the key emissions variable: choosing the 'key' emissions, and averaging across them to achieve a single emissions indicator that makes use of all relevant data for each facility.

Choosing which emissions are 'key': We want to include those pollutants which are of greatest environmental concern in the industry sector. The EPA indicates its judgment on

[4] Data integrity is guarded at this point by removing extreme normalised values, and then requiring that sector averages in each variable contain data from at least three companies. Extreme values arise mostly from erratic numbers self-reported in the AERs, and we have attempted to pre-exclude those that seem clearly to reflect measurement error. Remaining outliers are screened using 'outer fence' values derived from inter-quartile range analysis.

[5] We divide each year's facility impact by the sector average for that impact across all sampled years, not the sector average for that year alone. We do this because many sector averages show distinct time trends, mostly downward; but we want the company's impact index to vary with its own performance without (in that respect) reference to performance relative to its sector.

this for each license holder when it specifies which emissions must be monitored and reported, for air, sewer (effluent), and surface water discharges. Other industry sources have been used as well in determining which emissions are key in each sector.

Averaging the emissions: The facility's value each year is a simple average of its individual emission amounts, each having been normalised (if a mass value) and expressed as a ratio with sector-average as described above. The advantage of this approach is that we utilise the available data on emissions the EPA and other authorities consider important for each facility. The disadvantage is that we compare companies using a measure whose component parts are not uniform across all firms. Ultimately, this approach adapts to and reflects the considerable heterogeneity in monitoring and reporting across firms in each sector.

The emissions considered to be 'key,' and included in the above construction when reported for a particular facility-year, are the following.

Metal fabricating: IDEM (2004) suggests the key emission for this sector is volatile organic compounds (VOCs) to air. The US EPA (1995a) also targets this, and in addition wastewater emissions of solvents, acids, and (for facilities that electroplate) heavy metals. The Irish EPA sets VOCs to air and the pH of sewer emissions as frequent reporting requirements (a third and a half of the facilities, respectively). Chemical oxygen demand (COD), suspended solids, and zinc also frequently appear in the sewer emission requirements. Thus the key emissions performance variable in metal fabricating incorporates any of the following that are reported: *VOCs* (measured as carbon) for air; and *pH*, *COD*, *zinc*, and s*uspended solids* for water.[6]

Paints and inks: The greatest environmental impacts of this sector arise from the emission of VOCs to air during use, not manufacturing, of the product (ERI, 2004). Nevertheless, in paint manufacturing, VOCs are released when solvent-based raw materials, intermediate stages, and end product are exposed to air (in mixing or transfer) or water (particularly during clean-up). In addition, particulate matter containing VOCs and heavy metals (when present in raw material) can be released to air during grinding of pigments and to water during clean-up. From among these emissions of concern, we define key emissions for paint and ink facilities to incorporate the following that are frequently reported in the IPC records: *VOCs* to air; and *pH*, *COD*, *zinc*, and s*uspended solids* in water.

Wood sawmilling and preservation: The most significant environmental impact is from the pressure treatment chemicals forced into the wood for preservation (Environment Canada, 2002). Traditional methods can release chromium, copper, and arsenic (a known carcinogen) to ground or surface water through treatment, drip drying, storage, and disposal. Prior to treatment, bark removal and wood cutting emit large quantities of sawdust, which may create waterborne and airborne solids (US EPA, 1995b). The

[6] For each of the emission components except pH, higher values indicate greater impact and worse environmental performance. For meaningful inclusion with the others, we set a pH value of 7.5 as the centre of an acceptable range for facility waste water (Hutchinson, 2008; Palmer, 2008), and define the corresponding performance indicator as the absolute value of the difference between 7.5 and a facility's annual pH measure.

following are frequently reported in the EPA's records for these facilities: *pH***,** *COD*, s*uspended solids*, *copper*, *chromium,* and *arsenic* to water.

A complication is that wood products facilities' emissions are reported only in flow units (mg/litre of waste water), while in the other two sectors emissions are reported far more frequently in mass units (kg/year). We would like to have a common emissions variable across all three sectors. Therefore, we have created a blended Key Emissions variable for the full sample, equal to the mass measure for metals and paints and the flow measure for woods facilities. Since all are expressed as ratios with the facilities' sector averages, the mass and flow measures are comparable in showing each facility's performance relative to its peers. We divide the mass measure by employment to normalise, while the flow measure is normalised already and is not affected by the scale of operation in a given facility and year.[7]

The Key Emissions variable as constructed averages 1.0 within each sector. To give a feel for the measurement system being used, Table 1 backs up a step and shows how the sectors differ in the elements underlying Key Emissions.

Place Table 1 about here.

[7] The only potential bias from the different normalisations is that technology change over time might increase productivity. If output per worker rises, then all else equal, so will mass emissions. With mass emissions in the numerator and employment in the denominator, then, the measure may be biased upward as technology changes over time. But our hypothesis is that changing technology will reduce (normalised) emissions. Thus the measure tilts the scales against our hypothesis. We conclude that blending mass and flow emissions from the sectors into a single variable will not bias the analysis in favor of our hypothesis.

3.2 Waste

Waste is classified in the IPC facility documents as either 'hazardous' or 'non-hazardous' depending on the severity of its potential impacts; and its ultimate handling is classified as involving 'recovery' via some kind of treatment and reuse, versus 'disposal' to the environment (e.g., via incineration or land filling). Combinations of these disaggregated variables have been used to create three environmental performance variables in waste, each expressed as ratios with their respective sector averages: Total waste (normalised by employment), percentage of total waste that is disposed, and percentage of total waste that is hazardous (no normalisation required for the latter two). Again, these final facility variables expressed as ratios with their sector averages must average to 1.0 across each sector, and we provide a look at the underlying sector waste differences by showing the sector averages themselves in Table 2.

Place Table 2 about here.

It is possible that the difference between the wood products sector and the other two in total waste reflects reporting errors or inconsistencies. It is common for otherwise-wasted wood byproducts to be collected and used as kiln fuel onsite, and examining company records suggests that some may treat this as 'waste' while others do not. On the other hand, the relatively low hazardous waste percentage in woods suggests the progress made by these facilities in substituting more benign preservatives for toxic ones, a suggestion that seems to be borne out in the statistical tests reported later.

3.3 Resource usage

The EPA asks licensed facilities to report the annual use of electricity, fuel, and water in the AERs. We construct a variable for each, again normalised relative to employment for comparability purposes, and expressed as a ratio to the relevant sector average for cross-sector analysis. For statistical analysis we use variables for water, electricity end-use, and 'primary fuels,' where the latter converts all fuel amounts to MWh equivalents (Carbon Trust, 2008)[8] and sums MWh for each facility-year across fuel sources. What the energy variables measure is (the inverse of) energy efficiency; we assume that usage in MWh provides a reasonable proxy for environmental impact (Carbon Trust, 2008).[9] Like for waste, above, we present the sector averages themselves in Table 3.

Place Table 3 about here.

4 Measuring environmental practice

Firms take actions that may affect environmental performance, purposefully or otherwise, and we refer to such actions as 'practices.' IPC licensing resulted in documentation of an extraordinary number and range of environmental practices. We distinguish between practices involving technology and those characterised by organisational systems or activities. We refer to the latter as 'management practices.'

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[8] Carbon Trust's conversion factors, in kWh/m3 except as noted, are: natural gas, 10.9; diesel oil, 10,900; kerosene, 10,300; LPG, 7100; fuel oil, 11,900; and coal, 7472 kWh/tonne.

[9] One could be more precise about at least one environmental impact, by estimating tons of CO_2 per facility from the electricity and fuel totals in MWh. In addition, a total energy efficiency variable could combine end-use electricity and primary fuels. Both would require adjusting purchased electricity for national electricity-generation primary fuel mix and average transmission losses, and are beyond the scope of the present study.

4.1 Management

There are three kinds of management practices that might affect environmental performance, by influencing the firm's ability to identify and act upon factors that can affect its environmental impacts: planning, training, and procedural. We develop measures of each by identifying and scoring discrete reported activities or projects of the appropriate type.

Planning: This variable relates not to 'planning' *qua* orderly execution of pre-determined activities, but rather to processing of and/or search for information in the course of evaluating possible courses of action. We use information from the AERs' Environmental Management Plans (EMPs) for ongoing and future pollution reduction, and from the correspondence files, to construct a variable to capture planning actions related to environmental performance. We score reported planning projects based on the degree to which concrete goals or targets are specified; relevant data or information is used to factor past experience systematically into decision making; and there is evidence of follow through. For each facility-year, the value of the management planning variable is the sum of the year's projects, each scored 1-3:

> *3 (specific target + use of data + follow through); or*
>
> *2 (target + (data OR follow through)); or*
>
> *1 (target OR data OR follow through).*

Training. By disseminating information about environmental impacts, technologies, and/or management systems, employee training programs may affect companies' environmental performance. We score training programs according to their concreteness and the extent to which they appear to drive changes in employee behaviour. For each facility-year, the value of the management training variable is the sum of the year's projects, each scored 1-5, with points given as follows:

1 (baseline for a reported programme) + 0-2 (extent to which driving change) + 0-2 (degree of concreteness/specificity).

Procedures. Sample companies must track, record, and report regulated activities and outcomes. Such procedural activities may affect environmental performance by providing information on which impact-reducing steps can be based and evaluated. We create and combine two components. For one, we quantify the timeliness and completeness with which EPA monitoring, record keeping, and reporting requirements are met in the company's AER (EPA, 1997). We consider timeliness and completeness for summary emissions data in EPA format; Pollution Emissions Register data in EU-defined format; waste data along hazardous-nonhazardous and disposed-recovered dimensions; the EMP; and resource usage data on electricity, fuel, and water. This component of each company's annual value for the procedural variable is an AER score between 0 and 11:

1 (if turned in) + 0-2 (no-fair-good summary emissions data) + 0-2 (no-fair-good PER data) + 0-2 (no-fair-good waste data) + 0-2 (no-fair-good EMP) + 0-2 (no-fair-good resource usage data).

Another procedural component is EPA non-compliance notifications of a procedural (rather than pollution-oriented) nature. These notifications use a fairly precise set of phrases to indicate the degree of severity assigned to each non-compliance by the regulatory agency. These phrases are used to create a severity-weighted sum of the year's procedural non-compliances, as a component of each company's annual value for the management procedural variable:

*4 * (# with prosecution) + 3 * (# with threat of legal action) + 2 * (# with threat of further enforcement) + 1 * (# with no threat)*

The facility-year value for the management procedural variable is the sum of these AER and procedural non-compliance scores.[10] Table 4 shows sector averages for these management practice variables, in addition to a combined variable formed from the sum of the three. By two of three individual indicators and their composite, the paint and ink manufacturing facilities appear to exhibit a higher level of management practice. This impression is strengthened by some of the statistical results reported in section 5.

[10] There is some potential for double counting, as missing or incomplete AERs can generate notices of procedural noncompliance. But investigation shows that EPA inspectors exercise judgment in choosing how to deal with this kind of problem, and thus a noncompliance notification for inadequate AERs provides additional information beyond the AER deficiencies themselves.

Place Table 4 about here.

4.2 Technology

The license applications, AERs, and correspondence files contain information about what we refer to as technology 'projects': changes in the specific inputs, processes, and/or equipment by which outputs are created. Documentation arises when facilities seek EPA approval or advice on projects intended to reduce environmental impact, or ones with potential environmental implications that are considered for other reasons. There are two main challenges in transforming technology projects into appropriate practice variables: defining the variables for cross-sector analysis while capturing sector-specific characteristics; and representing the ongoing effects of prior years' projects.

4.2.1 Cross-sector technology matrix

For each sector, we create a matrix within which technology projects are located. One dimension of the matrix categorises projects according to a standard classification of pollution-prevention approaches. The other dimension of the matrix breaks down each sector's production process into major stages, according to available technical sources on that sector. This matrix makes it possible to test whether technological changes at particular points in the production process, or using particular pollution prevention approaches, are more or less important in improving environmental performance.

The key feature of the technology matrix is that the stage-of-production dimension is defined using sector-specific criteria, but within a generalised schema common to all sectors. This allows us to score technology projects using sector-specific criteria but compare them across sectors in analysing the data.

The pollution-prevention dimension of the matrix uses the following four categories (US EPA, 1995a,b):

- Raw materials – substitution with less polluting inputs, elimination
- Closing the loop – segregation and on- or off-site reuse of waste, product, and/or by-product
- Equipment changes – modification, replacement
- Process changes – not elsewhere counted

The stages-of-production dimension of the matrix uses five general categories: product design, preparation, basic production, finish work, housekeeping/other. Product design has to do with basic characteristics and may involve choice of more or less environmentally sensitive inputs; how the inputs are applied is scored at the appropriate later stage. (E.g., in metals, choice of low-VOC paint is scored in stage one; how the paint is applied is scored in stage four.) These five general stages are specified as follows in locating each sector's projects:

Metal fabricating. Given the sample's exclusion of facilities whose primary activities are casting or electroplating, the stages are (US EPA, 1995a; IDEM, 2004):

1. Product design – especially choice of the finish coating with respect to environmentally relevant characteristics

2. Metal shaping – cutting, grinding, forming, etc.
3. Surface preparation – cleaning, degreasing, etc.
4. Finish coating – application of painting, plating, etc.
5. Housekeeping/other – storage, cleaning, bunding, waste handling, packaging, etc.

Paints and inks. Typically pigments, base media, and other materials are obtained from suppliers and then prepared and blended at the facility (ERI, 2004; P2Rx, 2005):

1. Formulation – choice of base, pigments
2. Dry milling and mixing – drying raw materials combined prior to wet processing
3. Wet milling and mixing – further grinding and blending with wet materials
4. Filtering and filling – final product preparation for shipping
5. Housekeeping/other – storage, cleaning, bunding, waste handling, etc.

Wood sawmilling and preservation. Rough logs are prepared, cut, and treated for weather resistance (COFORD, 2004; Environment Canada, 2002; US EPA, 1995b):

1. Product design – choice of pressure treatment chemical; also, sourcing lumber from sustainably managed forests
2. Conditioning and cutting – debarking, pre-drying, sawing
3. Treatment – impregnation of cut wood with weather-proofing chemicals
4. Storage and drip – drying and storage of treated wood
5. Housekeeping/other – storage, cleaning, bunding, waste handling, packaging, etc.

Each project is assigned to the appropriate one among the 20 cells in the technology matrix for that facility-year – for example, a raw materials substitution in the finishing stage of production. The projects are scored on a scale of 1-5, depending on their nature and scope:

1 = End-of-pipe, small scale (e.g. bunding, over-ground pipes and tanks, dust filters)

2 = End-of-pipe, medium to large scale (e.g. waste water treatment plant (WWTP), incinerator)

3 = Clean technology, less fundamental to production process and/or small scale (e.g. recycling paper, pallets etc; inventory control)

4 = Clean technology, medium role in process and/or scale (e.g. RM substitution; heat recovery unit)

5 = Clean technology, more fundamental to production process and/or large scale (e.g. solvent distillation and re-use plant-wide; product development/re-design)

Clean technology projects are those judged to prevent or reduce environmental impacts (emissions, waste, and resource use) at the source; end-of-pipe, in contrast, entails controlling a given impact once created (Christie and Rolfe, 1995). Scale refers to the extent of the project's effect relative to that portion of the facility's activity to which it could apply.

An example can illustrate the use of the technology matrix. In 1998, metals facility 1 switched from a solvent based paint to a non-solvent powder coating for most of its finished products. This is a raw materials change in terms of pollution prevention approach, at the product design stage. The project is assigned a score of 4 – clean technology, applied to most but not all products – and this is added to the total in the raw materials change – product design stage cell of the matrix for that facility-year.

All project scores in each matrix cell for each facility-year are added together. These disaggregated cells are combined as desired to create the corresponding technology practice variables. In the empirical work reported below, we have aggregated facility-year cell totals across production stages, and alternatively across pollution prevention approaches. For example, we test the effectiveness of loop closing projects at all production stages, or of projects at the preparation stage across all pollution prevention approaches. The algorithm for turning these project matrix cells into technology practice variables has to do with impact over time, to which we now turn.

4.2.2 Ongoing effects of prior years' projects

Technology projects affect performance *cumulatively* over time. But these effects decrease over time, as equipment depreciates, and as the fit between projects and the surrounding production systems in which they are embedded becomes less precise due to changes elsewhere. A large literature suggests that technology investments do not affect performance fully in the year of their implementation, and that once fully operational the ‘efficiency schedule’ of investment entails an approximately ten percent annual rate of decay in impact (Doms, 1992).

While this literature deals primarily with fixed investment, in our data equipment projects represent less than half (about 40%) of the total. It is likely that there is less persistence in the effects of non-fixed technology projects. Therefore, we transform the summed projects from the technology matrix cells into technology practice variables assuming five year project lifetimes. Each new project’s score enters the variable at half its value in its first year, full value the second, then 75, 50, and 25 percent of the original value in project years three, four, and five. Let us designate the summed projects from a particular technology matrix cell or cells as ‘$PROJS_{it}$’—for example, all equipment-related projects, or all middle-stage projects for company *i* in any year *t* in the panel ($t \leq 9$). The corresponding technology practice variable $TECH_{it}$ is defined as follows:

$$TECH_{it} = .5PROJS_{it} + \sum_{\tau=1}^{4} (1.25 - .25\tau) PROJS_{t-\tau} \quad .$$

The first term is the current year’s (*t*) projects, and the following ones (inside the summation) give the decreasingly weighted projects from the prior year (*t-1*) back to the fourth year prior; projects from years further back, their five-year lifetimes having expired, are dropped. $TECH_{it}$ reflects the cumulative influence of the active technology stock, with the most recent projects (excepting the current year) weighted heaviest.

The weighted technology matrix approach as introduced here is designed so that technology practice variables are scored using sector specific criteria, but the same set of variables is shared sample-wide for cross-sectoral analysis. The aim, as with the environmental performance and management practice variables discussed earlier, is to facilitate both inference of cross-sector dynamics and exploration of distinctions among the relationships at the sector level. Table 5 shows the sector averages, including a composite variable given by the sum of approaches or stages (either delivers the same total, summing across the rows or columns of the weighted technology matrix).

Place Table 5 about here.

Table 5 shows that like in management, the paints sector has the highest total for technology practices. Equipment investment is the most heavily used pollution prevention approach across the sectors, and the paints facilities' composite advantage is maintained in equipment.

5 Modeling the determinants of environmental performance

In this section, we test the usefulness of these indicators in exploring the relationships between environmental performance and management and technology practices. We begin with the three sectors combined, moving from highly aggregated to finer-grained practice measures. The following sub-section then explores differences and similarities among the three sectors.

5.1 Cross-sectoral relationships

First we examine the relationship between aggregated practice and performance variables. The management and technology composite variables are used; on the environmental impact side, we use key emissions, total waste, and resource usage in electricity, fuel, and water summed into a composite. The statistics are Spearman's rank-order correlations.[11] Facilities' management and technology practice values are themselves correlated (Spearman's correlation of .351, significant at 1%). Therefore, in looking at the correlations between each kind of practice and performance, we use 'partial correlation' to control for the effects of the other practice – for example, the Spearman's correlation between emissions and management practice, controlling for (holding constant, or removing) the effect of technology. We also control for the year in all tests, since many of the variables exhibit time trends that may or may not be related to the relationships of interest.

Table 6 shows the most aggregated statistical associations.[12] While the hypothesised relationships are negative, we use a two-tailed significance standard to incorporate the possibility of unanticipated positive relationships as well. The management composite is,

[11] We have chosen nonparametric statistical techniques for the following reasons. First, scatter plots of the data show that it does not conform even approximately to the usual assumption of normal distributions. Related, many of the variables exhibit numerous extreme values, which can seriously bias parametric estimates. (We have attempted to distinguish between measurement or recording errors, to be corrected or excluded, and potentially legitimate values, of which we retain all but the most extreme as indicated by interquartile ranges.) In addition, it is difficult to specify *a priori* the functional form of many of the relationships of interest. Finally, we cannot confidently attribute meaningfully uniform intervals to the values arising from the data construction methods described in this study, and hence we employ where appropriate analytical techniques based on rank-ordering.

[12] The different numbers of observations in the columns of Table 6 reflect the partial correlation calculation process, which begins with a set of simple correlations using only observations for which there is data on all three (here) variables of concern – e.g., in column one, emissions, technology, and management.

as expected, negatively correlated with emissions at a 5% level of statistical significance; the technology – emissions correlation is weaker. Combined management practice may be weakly correlated with reduced waste and resource use as well, although not at an accepted level of statistical significance.[13]

Place Table 6 about here.

An example of unanticipated directionality is the positive correlation between technology and both total waste and combined resource use. This unexpected result could reflect reverse causality, with facilities generating high waste levels and/or resource usage undertaking technology investments intended to reduce them. Although there is a persistence effect built into the technology variables, a sufficient lag in efficacy of these investments could complicate inferences about the direction of causality.

A comprehensive examination of the unexpected technology-waste and impact association is beyond the scope of this paper; see Goldstein et. al (2009) for relevant results. But it is possible that disaggregating the measures may shed some light by seeing if certain kinds of technology projects are driving the unexpected relationship. Since that will explore the usefulness of the measurement methodologies introduced in this study, we turn there next.

[13] To conserve space, we test the determinants of total waste and combined resource use only, and not the more detailed waste and resource indicators.

We start with by disaggregating management practice into procedures, planning, and training. To economise on degrees of freedom, in each partial correlation of a disaggregated management category we control for other management disaggregates singly and for the aggregate technology variable, and vice versa.

Place Table 7 about here.

Table 6's negative relationship between emissions and combined management categories is shown in Table 7 to be driven by procedural and planning related management activities. Indeed, training related management practice shows an unexpected positive partial correlation with emissions, and this extends to total waste as well. It is possible that here as well, a kind of reverse causality is in effect.

Tables 8 and 9 present corresponding partial correlations between aggregate environmental impact measures and technology, disaggregated alternatively by approach to pollution prevention and stage in the production process.

Place Tables 8 and 9 about here.

Emissions are negatively associated with two of the technology approaches in Table 8, one strongly and one weakly, and with two of the technology stages in Table 9; but there is a positive correlation with equipment investment when breaking down technology by approach and with basic processing when disaggregating by stage of production. As for waste, we can now see that its unexpected positive correlation with technology at the aggregate level (Table 6) appears to be driven most consistently by a rather strong positive correlation with equipment investments (Table 8). Resource usage, on the other hand, shows a broad positive association with technology categories across the board.

5.2 Sector-specific relationships

In Table 10 we look sector by sector at the broad correlations reported for the full sample in Table 6, between environmental impact types and combined technology and management practices.

Place Table 10 about here.

The sectoral breakout reveals more differences regarding the puzzle of the positive technology-environmental impact correlation in the full-sample results. This positive association shows up most strongly in the wood products sector. The metal fabricating sector also exhibits the pattern found in the full sample results, for technology vs resource use and perhaps (although weakly) for total waste. But the paint and ink sector does not display this positive correlation.

On the other hand, the generally negative full-sample association between combined management categories and the environmental impact variables is shown in Table 10 to be distributed widely, although inconsistently, across the three sectors. Lower emissions are significantly related to higher management scores for wood and paint and ink facilities, but not for metals. Lower resource use may be weakly linked to management practice for metal facilities but not the others. And total waste shows a hint of this negative association only in the wood products sector, although not at a statistically significant level.

A finer-grained look is provided in Table 11, which reports partial correlations for individual management and technology practice categories by sector. In the interest of space, we report only results that are at (P≤10%) or near (P≤20%) statistical significance; full results are available from the authors.

Place Table 11 about here.

In general, Table 11's sector level disaggregation shows that management practices appear to exhibit intended outcomes more consistently in the paint and ink sector than in the other two. Even training and development, which for the full sample correlates positively with emission and waste impacts, in paints is either associated with reduced impact (waste) or no effect. This may suggest that managers in the paints facilities are deploying training programs proactively, not in reaction to environmental problems as they arise. In metals and wood products, the results on training continue to raise the question of whether a reverse-causality scenario, a lack of efficacy, or both are at work. On the other hand, procedures and planning, and in paints all three management variables, tend to correlate negatively with the environmental impacts they are intended to reduce.

With respect to disaggregated technology practices at the sector level, perhaps the most striking result in Table 11 is that in no sector, and for no environmental impact measure, is equipment investment associated with improved environmental performance. All of the statistically significant or near-significant correlations between equipment investment and impacts are positive. The paint sector is the only one not exhibiting this association, suggesting once more the possibility of a more purposeful, less reactive management dynamic. Again, these sectoral results themselves leave open whether the positive associations in metals and woods indicate unintended and unwanted consequences, a reverse-causality sequence, or some combination of the two.

Other technology effects, both by pollution prevention approach and by process stage, are mixed across sectors and environmental impact measures. There may be a weak indication that technological efforts focused at more fundamental changes, involving the composition of the product itself (product design stage) and/or of the materials employed (raw materials approach), tend more to be associated with environmental impact reduction. This result would be consistent with a stylised fact reported frequently in the literature, that ‘cleaner technologies’ – those aimed at reducing impacts at the source rather than cleaning them up at the ‘end of the pipe’ – are most promising.

6 Conclusion

This paper has introduced a new methodology for quantifying facility level practices, both managerial and technological, that might affect environmental performance. We have also built upon the considerable existing literature on indicators of that environmental performance. Our approach defines and measures practices and performance based on sector characteristics, but in a way permitting cross-sectoral comparison and analysis. This should allow researchers, policy makers and managers to look for evidence about what works at the very specific level, as well as for broader regularities at various levels of aggregation. The methodology can be implemented in any country whose environmental authority has gathered the detailed information entailed in IPC (now IPPC) licensing.

Among the Irish manufacturing facilities studied, statistical analysis of these indicators offers preliminary insights into the practice-performance relationship. At a high level of aggregation, organisational choices in management (more weakly in technology) are associated with improved performance with respect to the emissions that are key for facilities in each sector. With respect to waste and resource use, aggregate analysis reveals an unexpected association between greater practice and higher impact. Regarding both the expected and the unexpected broad results, the methodology and data permit a finer grained look at individual sectors and at specific kinds of managerial and technology practice. This more detailed analysis suggests in a preliminary way the operation of a reverse-causality process, whereby environmental impact problems stimulate increased activity aimed at reducing those impacts; this seems especially true for technology equipment investments in the metals and woods sectors. Facilities in the paints sector exhibit especially strong relationships between greater managerial effort and reduced environmental impact. Finally, there may be indications that changing the composition of products and/or materials is better able to reduce environmental impacts than other technology changes that take those as given.

There are additional questions and avenues that can be investigated using these methods and data. First is to explore further the positive environmental practice – impact relationship where it appears. An important step there will be to exploit the time series dimension of the data; a reverse causality explanation would suggest that the positive correlation between impacts and practices would disappear if we relate impact to lagged practice. In addition, results from case interviews and a survey undertaken with sample firms can be brought to bear to deepen our understanding of the organisational dynamics underlying the patterns appearing in the statistical analysis. Goldstein et al. (2009a) contains these time series and case and survey based extensions.

An important extension based on the data reported here is to explore the possibility that firms differentially exhibit underlying ‘organisational capabilities’ that complement the efficacy of observed practices (for example, Christmann, 2000; see Goldstein et al., 2008). Finally, the environmental indicators can be linked to financial data to apply these results to the question ‘does it pay to be green?’ (for example, Hart and Ahuja, 1996; Wagner et al., 2001; see Goldstein et al, 2009b). All of this work will need to account for the possibility of unobserved cross-firm heterogeneity (King and Lennox, 2001). The methodology introduced here is well suited to all of these extensions.

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Table 1 Sector Averages: Disaggregated Emissions Performance

	Metals	Paints	Woods
Carbon to air- flow	193.9		
COD to water- flow	83.0	55.8	40.0
Suspended solids- flow		8.99	21.5
Zinc to water- flow			
pH performance	0.634	0.289	0.301
Carbon to air- mass	59.0	39.1	
COD to water - mass	8.04	2.47	
Suspended solids- mass	0.582	0.473	
Zinc to water- mass	0.119		
Copper to water- flow			0.376
Arsenic to water- flow			0.256
Chromium to water- flow			0.147

Notes:
1. Averages are computed across all company-years.
2. Flow amounts are self-normalised (mg/m3 to air, mg/l to water).
3. Mass amounts are kg/year, normalised per employee.
4. pH is expressed as deviation from 7.5 (absolute value).
5. Missing values reflect insufficient data (fewer than three companies in sector).
6. Extreme values are excluded using interquartile range method.

Table 2 Sector Averages: Waste Performance

	Metals	Paints	Woods
Total waste	7.97	6.05	173.19
Percent hazardous	14.8%	23.1%	5.7%
Percent disposed	32.8%	47.1%	40.3%

Notes:
Averages are computed across all company-years.
Total waste is in tonnes per employee.
Extreme values have been excluded using interquartile ranges.

Table 3 Sector Averages: Resource Performance

	Metals	Paints	Woods
Electricity end-use (MWh/employee)	12.36	10.02	42.32
Primary fuel (MWh/employee)	8.91	21.14	32.65
Water (m3/employee)	78.76	80.71	22.11

Notes:
Averages are computed across all company-years.
Total waste is in tonnes per employee.
Extreme values have been excluded using interquartile ranges.

Table 4	**Sector Averages: Management Practice**		
	Metals	Paints	Woods
Procedures	-3.24	-1.20	-1.68
Planning	3.72	3.20	2.45
Training & Development	1.28	1.85	0.51
Composite (Sum)	*2.28*	*5.00*	*2.54*

Table 5	**Sector Averages: Technology Practice**			
		Metals	Paints	Woods
Approaches	Raw materials substitution	3.50	2.40	1.67
	Closing the loop	2.41	4.33	2.59
	Equipment investment	4.75	6.20	5.55
	Process change NEC	2.60	2.05	3.04
Stages	Product design	0.46	2.06	1.59
	Preparation	2.87	1.59	3.62
	Basic production	2.06	3.70	3.99
	Finish work	4.05	0.64	1.42
	Housekeeping/other	4.03	6.99	2.17
	Composite (Sum)	*13.26*	*14.98*	*12.85*

Table 6 Full-sample Partial Correlations: Environmental impact vs organisational practice			
(Probability values in parentheses)			
	Key emissions N=126	Total waste N=125	Combined resource use N=70
Technology (all categories, controlling for management & year)	-.141 (.118)	.233*** (.009)	.419*** (.000)
Management (all categories, controlling for technology & year)	-.216** (.016)	-.126 (.166)	-.045 (.745)
***Significant at 1% level; **5%; *10% (two-tailed). Based on Spearman's rho.			

Table 7 Full-sample Partial Correlations: Environmental impact vs management categories[+]			
(Probability values in parentheses)			
	Key emissions N=126	Total waste N=125	Combined resource use N=76
Procedure (controlling for planning, training)	-.243*** (.007)	-.177* (.053)	.058 (.629)
Planning (controlling for procedure, training)	-.225** (.013)	-.110 (.231)	-.149 (.210)
Training (controlling for procedure, planning)	.200** (.027)	.185** (.042)	.054 (.655)

***Significant at 1% level; **5%; *10% (two-tailed).
[+]Each partial correlation also controls for year and aggregate technology.
Based on Spearman's rho.

Table 8 Full-sample Partial Correlations: Aggregate environmental impact vs technology by approaches[+]			
(Probability values in parentheses)			
	Key emissions N=126	Total waste N=125	Combined resource use N=76
Raw materials (controlling for others)	.017 (.854)	-.069 (.453)	.230* (.054)
Closing loop (controlling for others)	-.239*** (.008)	.068 (.459)	.075 (.535)
Equipment (controlling for others)	.184** (.043)	.338*** (.000)	.259** (.029)
Process, NEC (controlling for others)	-.219** (.016)	-.155* (.090)	.227* (.057)

***Significant at 1% level; **5%; *10% (two-tailed).
[+]Each partial correlation also controls for year and aggregate management.
Based on Spearman's rho.

Table 9 Full-sample Partial Correlations: Aggregate environmental impact vs technology by stages			
(Probability values in parentheses)			
	Key emissions (N=126)	Total waste (N=125)	Combined resource use (N=70)
Product design (controlling for others+)	.014 (.880)	-.101 (.275)	.105 (.386)
Preparation (controlling for others+)	-.242*** (.008)	-.033 (.720)	.014 (.910)
Basic processing (controlling for others+)	.218** (.017)	.105 (.257)	.410*** (.000)
Finish work (controlling for others+)	-.028 (.759)	.223** (.015)	.177 (.143)
Housekeeping/other (controlling for others+)	-.237*** (.009)	.195** (.034)	.301** (.011)

***Significant at 1% level; **5%; *10% (two-tailed).
+Each partial correlation also controls for year and aggregate management.
Based on Spearman's rho.

Table 10 Partial Correlations By Sector: Environmental impact vs combined organisational practice				
(Probability values, observations in parentheses)				
Sectors	Practices	Impacts		
		Key emissions	Total waste	Combined resource use
Metal fabrication	Technology (all categories)	-.193 (.142, N=61)	.147 (.275, N=59)	.455** (.013, N=31)
	Management (all categories)	-.055 (.681, N=61)	.051 (.704, N=59)	-.149 (.142, N=31)
Paint & ink manufacturing	Technology (all categories)	-.182 (.249, N=44)	.044 (.804, N=36)	-.125 (.589, N=23)
	Management (all categories)	-.378** (.014, N=44)	-.115 (.516, N=36)	.228 (.320, N=23)
Wood products & treatment	Technology (all categories)	.240 (.323, N=21)	.404** (.033, N=30)	.510** (.021, N=22)
	Management (all categories)	-.450* (.053, N=21)	-.240 (.219, N=30)	-.053 (.823, N=22)

***Significant at 1% level; **5%; *10% (two-tailed).
Based on Spearman's rho.
+Technology partials control for management, and vice versa; both control for year.

Table 11 Partial Correlations By Sector:
Environmental impact vs disaggregated organisational practice

(Correlations with [10% < P values ≤ 20%] in parentheses; *positive correlations in italics*)

	Key emissions	Total waste	Combined resource use
Metal fabrication	Management *Training .255** Technology approach *(Equipment .184)* Process -.376*** Technology stage 2: Preparation -.470*** N=61	Management *(Training .223)* Technology approach *Equipment .302*** Technology stage None reportable N=59	Management Planning -.416** Technology approach None reportable Technology stage *3: Basic process .434*** *5: Housekeeping .655**** N=31
Paint & ink manufacturing	Management Procedure -.432*** Planning -.421** Technology approach None reportable Technology stage 5: Housekeeping -.387** N=44	Management Training -.303* Technology approach Raw materials -.408** *Loop closing .420*** Technology stage 2: Preparation -.383** N=36	Management *(Procedure .309)* *(Planning .332)* Technology approach None reportable Technology stage 2: Preparation -.518** *3: Basic process .672**** N=23
Wood products & treatment	Management Procedure -.415* Technology approach (Raw materials -.421) *(Process .351)* Technology stage 1: Product design -.542** N=21	Management Procedure -.341* *(Training .317)* Technology approach *Equipment .670**** Technology stage *4: Finish work .571**** N=30	Management None reportable Technology approach *(Equipment .423)* Technology stage *(1: Product design .410)* *4: Finish work .483** N=22

***Significant at 1% level; **5%; *10% (two-tailed).
Based on Spearman's rho.
Technology partials control for other technology categories, combined management, and year.
Management partials control for other management categories, combined technology, and year.