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Environmental performance and practice across sectors: methodology and preliminary results

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ABSTRACT

This paper introduces a new methodology for measuring and modeling manufacturers' environmental performance and the managerial and technological practices that affect it. Facility level licensing data are used to develop indicators based on sector-specific criteria but capable of being analyzed across sectors, at various levels of aggregation. This addresses the problem that environmental performance and determinants tend to be highly context-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. Word count = 10,049.

1. Introduction

In this paper, facility level data from the Irish Environmental Protection Agency (EPA) are used to develop and test 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 programme. 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 After, 2004, IPC was superceded by IPPC, Integrated Pollution Prevention and Control (European Union, 2005).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 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. By starting from facility level data and constructing measures scored on sector-based criteria, but capable of cross sector comparison, our approach also addresses a recurring theme in the relevant literature (discussed below) – that environmental performance and its determinants tend to be sector-specific, while modeling requirements and policy interests are often more general.

With respect to environmental performance, our methodology seeks a middle ground between single-indicator measures at a high level of generality and those that achieve context-specificity by focusing on individual impacts in single-sector analyses.

While our approach on environmental performance follows and extends somewhat a large literature, as discussed in Section 2, with respect to environmental practice we have had to break new ground. There is no research of which we are aware that develops detailed, quantitative representations of companies' technological and organizational 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.

Section 2 reviews the relevant literature, and ends with a statement of our major research questions. Section 3 describes the institutional setting and data sources for our study. In Sections 4 and 5, we introduce measures of environmental performance and of management and technology practices. Section 6 presents some preliminary empirical results in modeling the determinants of environmental performance, exploring the potential of the measurement methodology. Section 7 concludes with a discussion of the results.

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2. Literature review

As noted above, we draw upon a large literature on the measurement of environmental performance. Ultimately we are interested in how economic activities affect specific aspects of ecosystem quality (human and other organisms' health, non-biotic physical parameters). For example, King and Lenox (2002) proxy environmental performance by means of toxicity weighted emissions. But more typically, our information on these effects is limited, complex, and ambiguous. Thus, following standard practice (Dewulf and Van Langenhove, 2005), we focus instead on proximate environmental impacts in the form of emissions, waste, and resource usage. (We do make use of technical and scholarly literatures in determining which emissions are "most important" within each sector, as described in Section 4).

For comparability purposes, researchers have emphasized the importance of normalising such impacts. Typically this is accomplished by expressing impacts per 'functional unit' of output (MEPI, 2001, p. 29). Unfortunately, often information on output is not available (as establishd by Duffy et al., 2003, with respect to the Irish IPC licensees in our study). Depending on data availability, it is sometimes possible to normalize by expressing impacts relative to those predicted in an industry wide regression (King and Lenox, 2002). In our case, we have had to rely upon available data that can proxy for output, as described in Section 4.

Another problem addressed in the literature is the tension between studying performance at the industry or even firm specific levels, where specific context mediates outcomes, versus at an aggregated or even single-indicator level where comparisons over time and/or across firms are facilitated in a more generalizable way (GEMI, 1998; MEPI, 2001; Dewulf and Van Langenhove, 2005). One important single-index approach is the Productive Efficiency (PE) indicator (Tyteca, 1999). PE uses linear programming techniques on sector data to define a 'productive frontier' with respect to combinations of resource input use, desired salable output, and undesired polluting output; each producer's PE can be compared to a maximum attainable PE frontier. Another important aggregate indicator is the Jaggi-Freedman (JF) index (Jaggi and Freedman, 1992). The JF index uses the same kinds of variables as PE, but for each producer an average of the variables is computed, which is then normalised per unit of output and expressed as a ratio with the best performer's value in that variable. A more recent approach is Fijal (2007), who uses measures of materials and energy flows to construct a single environmental impact index for specific technologies.

Various studies point out that despite the compactness of the aggregate indicators and their ability to generate uni-dimensional rankings among companies in a sector, valuable information may be lost in combining disparate variables, in terms of the links between specific producer actions and corresponding environmental results (see for example Young and Rikhardsson, 1996, p. 116.) For this reason, another basic approach to environmental performance measurement has been to disaggregate, studying particular normalized impacts within specific industry settings. A major, widely cited example is MEPI (2001).

There are also approaches that fall somewhere between single measure indicators, with their high degree of generality, and the highly context-specific measures focused on particular impacts and sectors. 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. (2009) 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 4. 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 organizational 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 this study we use such information, for IPC-licensed Irish manufacturers, to create environmental performance and practice variables and test their utility in analyzing the relationships between the two. The basic questions to be addressed are thus the following:

2.1. Research question one

Can we extend the literature by using IPC licensing information to create environmental performance measures that permit flexibility in moving between more and less aggregated indicators, building up from facility and sector-specific considerations while preserving broad comparability?

2.2. Research question two

Can we create corresponding measures of environmental practice, based on disaggregated facility level activities in the context of sector level best practices, but capable of comparative aggregation across industry sectors and practice categories?

2.3. Research question three

Are these measures useful in exploring the relationships between environmental practice and performance of IPC-licensed manufacturing facilities in a multi-sector setting?

Before addressing question one in Section 4, question two in Section 5, and question three in Section 6, we describe the information and manufacturing facilities used in the study.

3. Data sources and sample

3.1. 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, included the following key components:

3.1.1. 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 minimization…a priority objective' (EPA, 1996, p. 1).

3.1.2. 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[3] 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.

This combination of sources does much to alleviate problems of 'green-glossing' of self-reported information.[4] The AERs are prepared by managers or their hired consultants, and would be expected to paint where possible a rosy picture of environmental performance. But the abundance of EPA inspector reports and Agency-generated correspondence in the files offers a check, and provides information through which to filter claims by the regulated entities.

3.2. Sample selection

We organize our study around three industry sectors. For generalizability, we sought sectors exhibiting a range of technology, product and market characteristics.[5] 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:

3.2.1. 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.

3.2.2. 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.

3.2.3. 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, fiber 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.

We now turn to constructing measures of environmental performance and practice for these facilities.

4. Measuring environmental performance

4.1. Research question one

Can we extend the literature by using IPC licensing information to create environmental performance measures that permit flexibility in moving between more and less aggregated indicators, building up from facility and sector-specific considerations while preserving broad comparability?

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.[6] 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 analyze a wide range of possible relationships. The steps employed for all three impact measures to create this comparability (with exceptions as noted below) include normalization and within-sector averaging:

4.1.1. 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 normalize

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

[4] We thank an anonymous reviewer for this journal for pointing out this problem in the present context.

[5] Two additional factors facilitated linking the environmental data with financial results for future analysis. First, we favored 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.

[6] 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.

mass impacts relative to a proxy, the number of employees (available in financial reports at the Companies Registration Office).[7]

4.1.2. Within-sector averaging

Once the raw data are normalised, we calculate each annual facility environmental impact value as a ratio with its sector average.[8] 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.[9]

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

4.2. 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.

4.2.1. 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 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.

4.2.2. Averaging the emissions

The facility's value each year is a simple average of its individual emission amounts, each having been normalised and expressed as a ratio with sector average as described above. The advantage of this approach is that we utilize 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.

4.2.3. 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 *suspended solids* for water.[10]

Table 1
Sector Averages: Disaggregated Emissions Performance (Except pH, kg/year, normalised per employee).

	Metals	Paints	Woods
pH performance	.634	.289	No data
Carbon to air- mass	59.0	39.1	
COD to water - mass	8.04	2.47	
Suspended solids- mass	.582	.473	
Zinc to water- mass	.119	NA	

Averages are computed across all company-years. pH is expressed as deviation from 7.5 (absolute value). Extreme values are excluded using inter-quartile range method.

4.2.4. 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 *suspended solids* in water.

4.2.5. Wood sawmilling and preservation

Unfortunately, licensed facilities in this sector during this time period reported emissions only in "flow" units (e.g., concentration in mg/l). While representative flow sampling could theoretically provide already-normalised emissions measures, EPA advised that this could not be assumed, and hence the wood sector facilities are excluded from the emissions data and analysis.

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.

4.3. 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

[7] There is a potential bias from normalising by employment, in that technology change over time might increase productivity. If output per worker rises, then all else equal, so will environmental impacts. With mass impacts in the numerator and employment in the denominator, then, the measure may be biased upward as technology changes over time. But if one expects that changing technology will reduce (normalised) impacts, then the measure tilts the scales against what is expected. We conclude that normalising by employment will not bias the analysis in a way warranting concern.

[8] 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.

[9] 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.

[10] 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 wastewater (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.

Table 2
Sector Averages: Waste Performance.

	Metals	Paints	Woods
Total waste (tonnes/employee)	7.97	6.05	173.19
Percent hazardous	14.8%	23.1%	5.7%
Percent disposed	32.8%	47.1%	40.3%

Averages are computed across all company-years. Extreme values have been excluded using inter-quartile 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

Averages are computed across all company-years. Extreme values have been excluded using inter-quartile ranges.

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 normalization 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.

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 by-products to be collected and used as kiln fuel on site, 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.

4.4. 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 fuel the variable we create is 'primary fuels,' which converts quantities of all fuel types consumed at the facility to MWh equivalents (Carbon Trust, 2008)[11] and sums MWh for each facility-year across fuel sources. (In the statistical tests in Section 6, we use for the resource performance variable 'combined resource use,' the sum of the electricity, primary fuel, and water variables described here.) 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).[12] Like for waste, above, we present the sector averages themselves in Table 3 (Fig. 1).

Research question one has, we argue, been answered in the affirmative. We have used IPC-generated information to create facility level environmental performance measures based on sector-specific criteria; normalization makes them comparable over time and among industry peers, and sector averaging allows economy-wide comparability. Within each of the major areas – emissions, waste, and resource use – detailed impact measures can by analyzed separately, or combined as aggregate indicators.

Specific techniques in this approach are drawn from the literature; our contribution vis-à-vis research question one is to bring them together in a framework that is aggregationally flexible and based on data available in many EU settings. We turn now to less traveled ground, creation of similarly flexible and replicable environmental practice measures.

5. Measuring environmental practice

5.1. Research question two

Can we create corresponding measures of environmental practice, based on disaggregated facility level activities in the context of sector level best practices, but capable of comparative aggregation across industry sectors and practice categories?

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 characterized by organizational systems or activities. We refer to the latter as 'management practices.'

5.2. 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.

5.2.1. 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. For each facility-year, the value of the management-planning variable is the sum of the year's projects, scored according to 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.

5.2.2. Training

By disseminating information about environmental impacts, technologies, and/or management systems, employee training programmes may affect companies' environmental performance. We score training programmes according to their concreteness and the extent to which they appear to drive changes in employee behavior. For each facility-year, the value of the management-training variable is the sum of the year's projects, each scored according to the degree of specificity and the extent of change-creating follow-through.

[11] 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 kW h/tonne.

[12] 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.

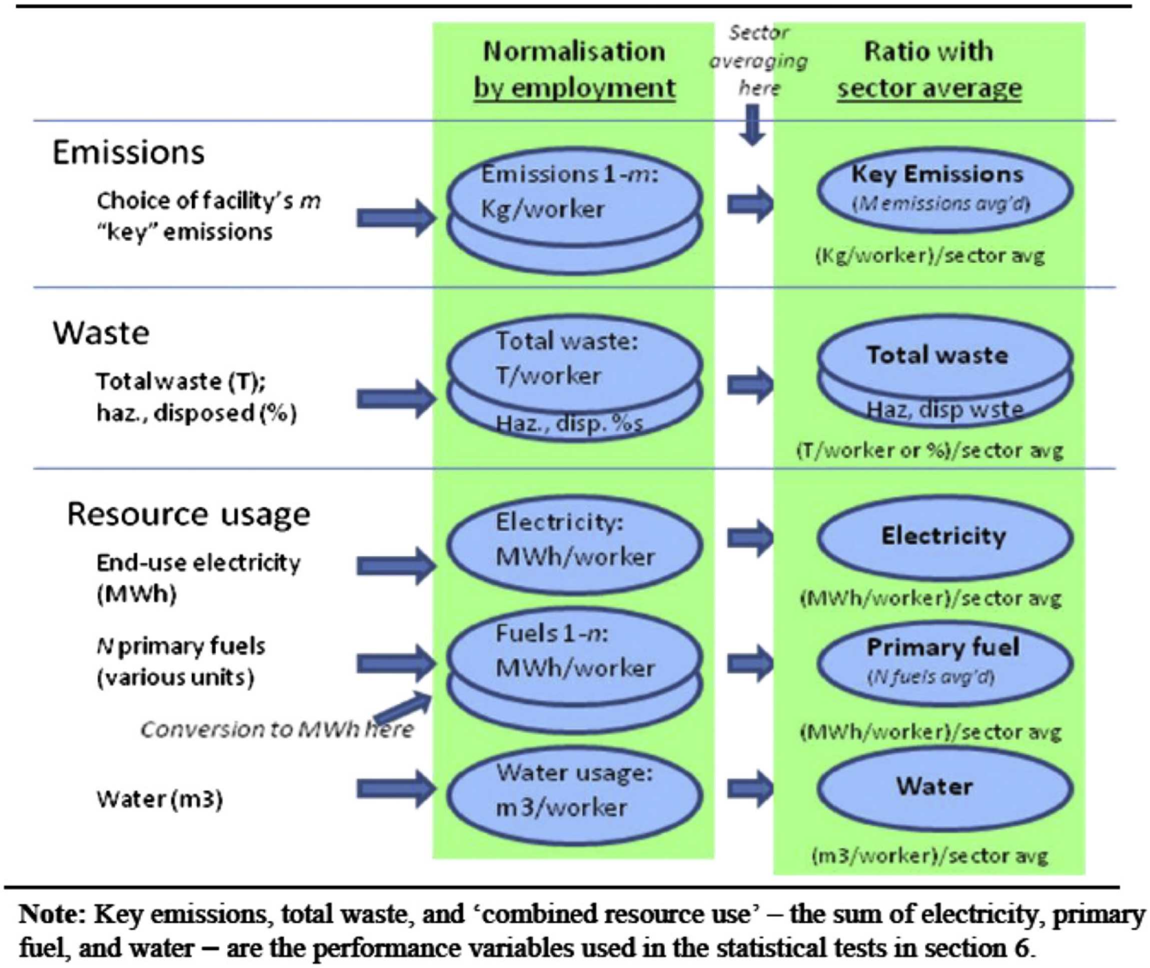

Fig. 1. Summarizes the steps taken to construct the environmental performance variables.

5.2.3. Procedures

Tracking, recording, and reporting of regulated activities and outcomes may affect environmental performance by providing information on which impact-reducing steps can be based and evaluated. We create and combine two components. One is the timeliness and completeness with which EPA requirements are met in the company's AER (EPA, 1997): the EMP and data on the various dimensions of emissions, waste, and resource usage. The other component is EPA non-compliance notifications of a procedural (rather than pollution-oriented) nature. The notifications use a standard set of phrases to indicate the degree of severity assigned to each non-compliance by the agency, which we use to create a severity-weighted sum of the year's procedural non-compliances. The facility-year value for the management-procedural variable is the sum of these AER (positive) and procedural non-compliance (negative) scores.[13]

Table 4 summarizes the scoring criteria used. An example of each variable, taken from Metals company 5 in 2001, may give a feel for how they are constructed. The facility undertook a planning project to assess means of segregating and recycling factory waste, scored 2 out of a possible 3 because its goal was specific and it made use of relevant data, but information on follow-through was lacking; along with four other planning projects that year, this generated a 2001 management-planning value of 9. In that year the facility implemented a (highly unusual) total of four training programmes, of which three received only one point due to a (very common) lack of specificity and follow-through, creating a facility-year management-training value of 6. Finally, the facility's 2001 AER was scored a rather middling 5 points, offset by a whopping negative 35 points of procedural non-compliance notices (one with threat of 'further enforcement,' and eleven with the more serious threat of 'legal action'), for a management-procedural value of 30.

Table 4
Scoring Criteria: Management Practice Variables.

	Planning	Training	Procedural
Execution (presence of project)	✓	✓	✓
Specificity & concreteness	✓	✓	
Use & quality of relevant data	✓		✓
Follow-through (extent of behavior change)	✓	✓	
EPA sanctions (weighted by severity)			✓

[13] Thus the management procedures value can be negative. There is some potential for double counting, as missing or incomplete AERs can generate notices of procedural non-compliance. But investigation shows that EPA inspectors exercise judgment in dealing with this kind of problem, and thus a non-compliance notification for inadequate AERs provides additional information beyond the AER deficiencies themselves.

Table 5
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	.51
Composite (Sum)	2.28	5.00	2.54

Table 5 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 6.

5.3. 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.

5.3.1. Cross-sector technology matrix

For each sector, we create a matrix within which technology projects are located. One dimension of the matrix categorizes 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 generalized schema common to all sectors. This allows us to score technology projects using sector-specific criteria but compare them across sectors in analyzing 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:

5.3.1.1. 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; 2) metal shaping – cutting, grinding, forming, etc.; 3) surface preparation – cleaning, degreasing, etc.; 4) finish coating – application of painting, plating, etc.; and 5) housekeeping/other – storage, cleaning, bunding, waste handling, packaging, etc.

5.3.1.2. 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; and 5) housekeeping/other – storage, cleaning, bunding, waste handling, etc.

5.3.1.3. 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 of treated wood; and 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 (end of pipe vs clean technology) and scope (how widespread within that portion of the facility's activity to which it could apply, and/or fundamental in the production process). 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).

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.

5.3.2. 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,

Table 6
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	.46	2.06	1.59
	Preparation	2.87	1.59	3.62
	Basic production	2.06	3.70	3.99
	Finish work	4.05	.64	1.42
	Housekeeping/other	4.03	6.99	2.17
	Composite (Sum)	13.26	14.98	12.85

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. Thus for a given facility and year, for a particular technology matrix cell or combination of cells – for example, all equipment-related projects, or all middle-stage projects – the corresponding technology practice variable reflects the cumulative influence of the active technology stock, with the most recent projects (excepting the current year) weighted heaviest and those more than five years old ignored.

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 6 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).

Table 6 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 – a pattern that turns out to be of great interest regarding the practice-performance relationship, as shown in the next section – and the paints facilities' composite advantage is maintained in equipment (Fig. 2).

Research question two has, we believe, also been answered in the affirmative. These environmental practice measures are based on fine-grained IPC information that, as in the environmental performance case, should be available in many EU settings. Sector-specific criteria are used to score highly disaggregated measures of management practice in three categories and technology practice along the two dimensions of process stage and type of approach. The shared structure of these rubrics makes management and technology practice values comparable across sectors, and the appropriate level of aggregation can be chosen to suit the analysis at hand.

Together with the previous section's results, this should allow the researcher to explore a wide range of empirical questions. The next section examines this expectation.

6. Modelling the determinants of environmental performance

6.1. Research question three

Are these measures useful in exploring the relationships between environmental practice and performance of IPC-licensed manufacturing facilities in a multi-sector setting?

There are at least two ways to test the usefulness of these indicators in exploring the relationships between environmental performance and management and technology practices. One is to look at individual companies' impact-reduction efforts, and see the extent to which both the impacts and the efforts, measured according to the indicators presented here, can be understood in ways that make sense in terms of what managers and regulators are saying in each case. In Hilliard et al. (2010) we pursue this line of inquiry, with results that answer research question three affirmatively. Another approach is to see whether broad, statistical practice-performance relationships can be made sense of, using these measures, on an *ex-ante* basis. That is the tack we take in the present study.

We begin with the three sectors combined, moving from highly aggregated to finer-grained practice measures. The following

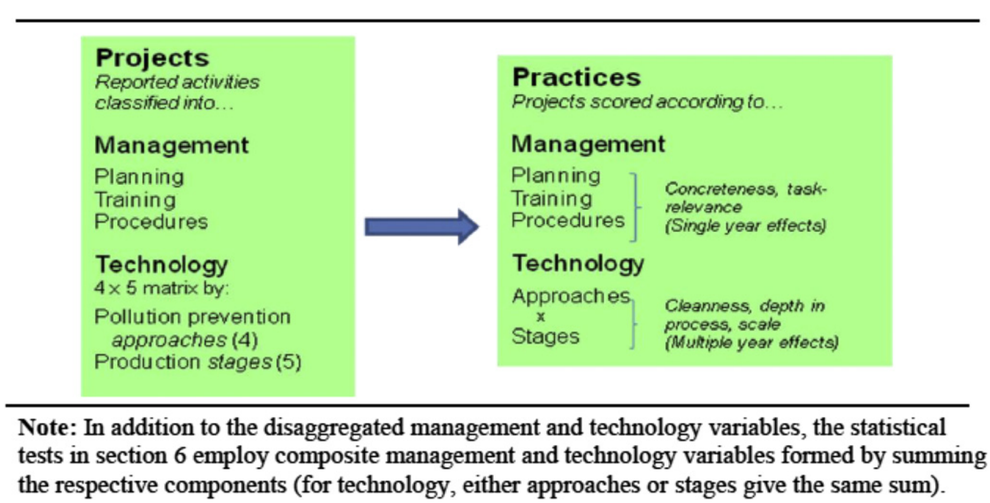

Fig. 2. Summarizes the steps involved in constructing the management and technology practice variables.

Table 7
Full-sample Partial Correlations: Environmental impact vs organizational practice (Probability values in parentheses).

	Key emissions[d] $N = 105$	Total waste $N = 125$	Combined resource use $N = 70$
Technology (all categories, controlling for management & year)	−.196[b] (.047)	.233[a] (.009)	.419[a] (.000)
Management (all categories, controlling for technology & year)	−.179[c] (.071)	−.126 (.166)	−.045 (.745)

Based on Spearman's rho.
[a] Significant at 1% level (two-tailed).
[b] 5% (two-tailed).
[c] 10% (two-tailed).
[d] Key emissions includes only metals and paints sectors facilities.

sub-section then explores differences and similarities among the three sectors.

6.2. 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 composite resource usage (electricity end-use, primary fuels, and water summed). The statistics are Spearman's rank-order correlations.[14] 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 7 shows the most aggregated statistical associations.[15] While the most likely expected relationship would be negative, we use a two-tailed significance standard to incorporate the possibility of unanticipated positive relationships as well. Both the management and technology practice composites are, as expected, negatively correlated with emissions, at 10% and 5% levels of statistical significance respectively. Combined management practice may be weakly correlated with reduced waste as well, although not at an accepted level of statistical significance.[16]

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 that suffer from 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 Hilliard et al. (2009a) 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 further explore the usefulness of the measurement methodologies introduced in this study (research question three), we turn there next.

We start with by disaggregating management practice into procedures, planning, and training. To economize 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.

Table 7's negative relationship between emissions and combined management categories is shown in Table 8 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 9 and 10 present corresponding partial correlations between aggregate environmental impact measures and technology, disaggregated alternatively by approach to pollution prevention and stage in the production process.

Emissions are negatively associated with two of the technology approaches in Table 9, and with two of the technology stages in Table 10; 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 7) appears to be driven most consistently by a rather strong positive correlation with equipment investments (Table 9). Resource usage, on the other hand, shows a broad positive association with technology categories across the board.

Table 8
Full-sample Partial Correlations: Environmental impact vs management categories[d] (Probability values in parentheses).

	Key emissions[e] $N = 105$	Total waste $N = 125$	Combined resource use $N = 76$
Procedure (controlling for planning, training)	−.232[b] (.020)	−.177[c] (.053)	.058 (.629)
Planning (controlling for procedure, training)	−.228[b] (.022)	−.110 (.231)	−.149 (.210)
Training (controlling for procedure, planning)	.257[a] (.010)	.185[b] (.042)	.054 (.655)

Based on Spearman's rho.
[a] Significant at 1% level (two-tailed).
[b] 5% (two-tailed).
[c] 10% (two-tailed).
[d] Each partial correlation also controls for year and aggregate technology.
[e] Key emissions includes only metals and paints sectors facilities.

[14] 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 inter-quartile 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. Hence, we employ where appropriate analytical techniques based on rank-ordering.

[15] The different numbers of observations in the columns of Table 7 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.

[16] To conserve space, we test the determinants of total waste and combined resource use only, and not the more detailed waste and resource indicators. 45.

Table 9
Full-sample Partial Correlations: Aggregate environmental impact vs technology by approaches[d] (Probability values in parentheses).

	Key emissions[e] $N = 105$	Total waste $N = 125$	Combined resource use $N = 76$
Raw materials (controlling for others)	.037 (.713)	−.069 (.453)	.230[c] (.054)
Closing loop (controlling for others)	−.260[a] (.009)	.068 (.459)	.075 (.535)
Equipment (controlling for others)	.199[b] (.047)	.338[a] (.000)	.259[b](.029)
Process, NEC (controlling for others)	−.357[a] (.000)	−.155[c] (.090)	.227[c] (.057)

Based on Spearman's rho.
[a] Significant at 1% level (two-tailed).
[b] 5% (two-tailed).
[c] 10% (two-tailed).
[d] Each partial correlation also controls for year and aggregate management.
[e] Key emissions includes only metals and paints sectors facilities.

Table 10
Full-sample Partial Correlations: Aggregate environmental impact vs technology by stages (Probability values in parentheses).

	Key emissions[e] ($N = 105$)	Total waste ($N = 125$)	Combined resource use ($N = 70$)
Product design (controlling for others[d])	.014 (.891)	−.101 (.275)	.105 (.386)
Preparation (controlling for others[d])	−.302[a] (.002)	−.033 (.720)	.014 (.910)
Basic processing (controlling for others[d])	.167[c] (.099)	.105 (.257)	.410[a] (.000)
Finish work (controlling for others[d])	−.004 (.970)	.223[b] (.015)	.177 (.143)
Housekeeping/other (controlling for others[d])	−.232[b] (.021)	.195[b] (.034)	.301[b] (.011)

Based on Spearman's rho.
[a] Significant at 1% level (two-tailed).
[b] 5% (two-tailed).
[c] 10% (two-tailed).
[d] Each partial correlation also controls for year and aggregate management.
[e] Key emissions includes only metals and paints sectors facilities.

We will discuss these findings further in what follows. But first, we explore whether additional insights can be generated by examining these full-sample relationships on a sectoral level.

6.3. Sector-specific relationships

In Table 11 we look sector by sector at the broad correlations reported for the full-sample in Table 7, between environmental impact types and combined technology and management practices.

First, the correlation between combined technology practice and lower emissions, reported for the full-sample in Table 7, is shown in Table 11 to be shared between the metals and paints facilities with usable emissions data. (While the sectoral technology-emissions correlations are very close to the full-sample value, the smaller sample sizes reduce their statistical significance.) On the other hand, the full-sample association between combined management practice and lower emissions is shown in Table 11 to be driven by the paints facilities alone.

In addition, the sectoral breakout reveals more differences regarding the puzzle of the positive technology-environmental impact correlation in the full-sample results, for waste and resource impacts. This positive association shows up most consistently 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 not significantly) for total waste. But the paint and ink sector does not display this positive correlation.

A finer-grained look is provided in Table 12, 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 ($P \leq 10\%$) or near ($P \leq 20\%$) statistical significance; full results are available from the authors. For ease of interpretation, correlations at near-statistical significance are in parentheses, and positive ones (more practice − worse performance) are italicized.

In general, Table 12′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 programmes 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, where they exhibit significant values, 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 12 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 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 change, by involving the materials employed (raw materials approach), tend more to be

Table 11
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[a] (.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[a] (.014, $N = 44$)	−.115 (.516, $N = 36$)	.228 (.320, $N = 23$)
Wood products & treatment	Technology (all categories)	No data	.404[a] (.033, $N = 30$)	.510[a] (.021, $N = 22$)
	Management (all categories)		−.240 (.219, $N = 30$)	−.053 (.823, $N = 22$)

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

Table 12
Partial Correlations By Sector: Environmental impact vs disaggregated organisational practice (Correlations with [10% $<$ *P* values $\leq$ 20%] in parentheses; *positive correlations in italics*).

	Key emissions		Total waste		Combined resource use	
Metal fabrication	Management		Management		Management	
	Training	*.255*[c]	(*Training*	*.223*)	Planning	−.416[b]
	Tech. approach		Tech. approach		Tech. approach	
	(*Equipment*	*.184*)	*Equipment*	*.302*[b]	None reportable	
	Process	−.376[a]	Technology stage		Technology stage	
	Technology stage		None reportable		*3: Basic process*	*.434*[b]
	2: Preparation	−.470[a]	*N* = 59		*5: Housekeeping*	*.655*[a]
	N = 61				*N* = 31	
Paint & ink manufacturing	Management		Management		Management	
	Procedure	−.432[a]	Training	−.303[c]	(*Procedure*	*.309*)
	Planning	−.421[b]	Tech. approach		(*Planning*	*.332*)
	Tech. approach		Raw materials	−.408[b]	Tech. approach	
	None reportable		*Loop closing*	*.420*[b]	None reportable	
	Technology stage		Technology stage		Technology stage	
	5: Housekeeping	−.387[b]	2: Preparation	−.383[b]	2: Preparation	−.518[b]
	N = 44		*N* = 36		*3: Basic process*	*.672*[a]
					N = 23	
Wood products & treatment	No data		Management		Management	
			Procedure	−.341[c]	None reportable	
			(*Training*	*.317*)	Tech. approach	
			Tech. approach		(*Equipment*	*.423*)
			Equipment	*.670*[a]	Technology stage	
			Technology stage		(*1: Product design*	*.410*)
			4: Finish work	*.571*[a]	*4: Finish work*	*.483*[c]
			N = 30		*N* = 22	

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.
[a] Significant at 1% level (two-tailed).
[b] 5% (two-tailed).
[c] 10% (two-tailed).

associated with environmental impact-reduction. This result would be consistent with a stylized 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. In contrast, we note the concentration of correlations between technological activity and *greater* environmental impact in the later stages of production (Tables 10 and 12).

We believe these results confirm that the environmental performance and practice measures introduced here are capable of supporting useful, flexible empirical explorations, as asked in research question three. *Ex-ante* reasonable expectations (better practice improves performance) hold across much of the activity studied, and the exceptions (reverse causality) are fairly systematic and can be understood in equally reasonable ways. In the process, we learn much about what drives behavior and what seems to work best.

7. 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, and offers an opportunity to develop a rich empirical representation of what companies are doing to address environmental concerns.

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, organizational choices in management and 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 presence 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. Company level analysis (Hilliard et al., 2010) suggests that in general, and particularly in these two sectors, most managers avoid expensive steps like equipment purchases unless pressed, in this case by regulatory scrutiny of severe impacts. Ironically, facilities in the paints sector – with an especially long history of regulatory pressure around VOCs and related issues – do not exhibit the reverse causality phenomenon, having forged unusually strong managerial capabilities to control the relationships between organizational effort and reduced environmental impact.

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References

Carbon Trust, 2008. 'Energy and Carbon Conversions.' www.carbontrust.co.uk.

Christie, I., Rolfe, H., 1995. Cleaner Production in Industry. PSI Publishing, London.

COFORD, 2004. National Council of Forest Research and Development COFORD Connects: Processing/Products. No. 4.

Dewulf, J., Van Langenhove, H., 2005. 'Integrating industrial ecology principles into a set of environmental sustainability indicators for technology assessment'. Resources, Conservation and Recycling 43, 419–432.

Doms, M.E., 1992. 'Estimating Capital efficiency schedules within production Functions'. Centre for Economic Studies, 92–94. U.S. Bureau of the Census, CES.

Duffy, N., McCarthy, C., Zoehrer, M., 2003. Environmental Benchmarking for IPC Industries. Synthesis Report. EPA, Wexford, ISBN 1-84095-103-6.

Environment Canada, 2002. Wood preservation' in the green Lane. www.ec.gc.ca/toxics/wood-bois/pubs/assesmentsection4_e.html#_Toc504929728.

Environmental Protection Agency (Ireland), 1996. BATNEEC Guidance Note for the Chemical Sector.

Environmental Protection Agency (Ireland), 1997. IPC Guidance Note for Annual Environmental Report. Ardcavan: EPA.

Environmental Protection Agency (U.S.), 1995a. Profile of the Fabricated Metal Products Industry (Sector Notebook Project, September).

Environmental Protection Agency (U.S.), 1995b. Profile of the Lumber and Wood Products Industry (Sector Notebooks series).

ERI: Environmental Road-mapping Initiative, 2004. Paints and Coatings: Impacts, Risks and Regulations. National Centre for Manufacturing Sciences. http://ecm.ncms.org/ERI/new/IRRpaintcoating.htm.

European Union, 2005. The IPPC Directive. http://europa.eu.int/comm/environment/ippc.htm.

Fijal, T., 2007. 'An environmental assessment method for cleaner production technologies'. Journal of Cleaner Production 15, 914–919.

GEMI., 1998. Measuring Environmental Performance: a Primer and Survey of Metrics in Use. Global Environmental Management Initiative, Washington, D.C.

Hilliard, R., Goldstein, D., Parker, V., 2009. 'Testing environmental performance, practice, and capabilities,' Chapter 4. Final Report. In: Environmental Technology, Dynamic Environmental Capabilities and Competitiveness. Centre for Innovation & Structural Change (CISC), NUI Galway; and Environmental Protection Agency, Wexford; Ireland.

Hilliard, R., Goldstein, D., Parker, V., 2010. 'Evidence on Search Routines in Small and Medium Sized Companies'. Centre for Innovation & Structural Change (CISC), NUI, Galway, Ireland.

Hutchinson, J., 2008. Personal Communication. Department of Environmental Protection, Pennsylvania.

Indiana Department of Environmental Management (IDEM), 2004. Sector specific technology transfer Guide: metal products industry, March. www.in.gov/idem/oppta/p2/assessments/.

Jaggi, B., Freedman, M., 1992. 'An examination of the impact of pollution performance on economic and market performance: pulp and paper firms'. Journal of Business Finance and Accounting 19 (5), 697–713.

Karavanas, A., Chaloulakou, A., Spyrellis, N., 2009. 'Evaluation of the implementation of best available techniques in IPPC context: an environmental performance indicators approach'. Journal of Cleaner Production 17 (4), 480–486.

King, A., Lenox, M., 2002. 'Exploring the locus of profitable pollution reduction'. Management Science 48 (2), 289–300.

MEPI., 2001. Measuring the Environmental Performance of Industry. Final Report. European Commission, Brussels.

Palmer, J., 2008. Personal communication. Allegheny College Department of Environmental Science.

P2Rx, 2005. The paint and coating manufacturing Topic Hub. http://www.p2rx.org/topichubs/toc.cfm?hub=28andsubsec=7andnav=7.

Tyteca, D., 1999. 'Sustainability indicators at the firm level: pollution and resource efficiency as a necessary condition toward sustainability'. Journal of Industrial Ecology 2 (4), 61–77.

Wätzold, F., Büstman, A., Eames, M., Lulofs, K., Schuck, S., 2001. 'EMAS and regulatory Relief in Europe: lessons from national experience'. European Environment 11 (1), 37–48.

Young, C.W., Rikhardsson, P.M., 1996. 'Environmental performance indicators for business'. Eco-Management and Auditing 3, 113–125.