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Managing the environmental performance of production facilities in the electronics industry: more than application of the concept of cleaner production

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Abstract

This paper approaches the production facilities in the supply chain primarily from an Original Equipment Manufacturer's perspective as the requesting party in the scope of environmental quality and secondarily from a production facility's perspective. From the perspective of the customer as well as the supplier, aspects such as price, delivery, technology etc. play an ongoing role, while environmental quality is a new aspect. With respect to environmental quality, the paper discusses the existing situation in the facilities, like the use of environmental management systems, the notions of environmental performance, green procurement and environmental quality in relation to cost structures of facilities. The paper also introduces a new method of benchmarking environmental performances of facilities. Environmental performance expresses the total production behaviour of the production facility. A link into a business perspective is shown on the basis of the environmental performance. In this scope the result of a worldwide assessment of 25 printed board production facilities is discussed and a conclusion is drawn. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Business; Environmental performance; Environmental quality; Production facility; Supply chain

1. Introduction

A study of the environment of a company identifies customers, suppliers, competitors, shareholders, governments etc. Several relationships exist between the company and all these entities. Within this setting, a company operates in terms of product sales, production, procurement, legislation etc. Each company has one or more production facilities, which manufactures components and/or products. Each production facility generates environmental load in terms of contributions to environmental effects as, acidification, greenhouse effect, smog etc. In general a full product life cycle from "cradle to grave" comprises three phases: the product manufacturing phase, the product use phase and the recycling phase. Each phase generates environmental load, which can also be divided into three parts, see E_{L1} to E_{L3} in Fig. 1. The manufacturing phase comprises a large number of production facilities. Several customer-supplier relationships exist between the production facilities and these relationships are cornerstones of the global operating economic process. From the perspective of the customer as well as the supplier, aspects such as price, delivery, service, technology and quality play an ongoing role, while environmental quality is a new aspect, see Fig. 2. In the current global environmental developments in the electronics industry, the environmental quality of manufactured products and components

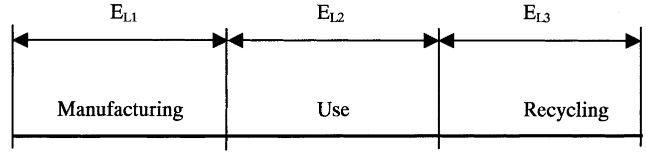

Fig. 1. The product life cycle.

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Fig. 2. Customer–relationship.

receives attention in terms of environmentally hazardous substances, recyclables and energy use. In this case, environmental quality is product-related and not production process-related. This paper approaches the environmental quality of production processes from a relative perspective. The environmental quality of a production process can be expressed by a numerical environmental performance. Based on environmental performance, the management of the production facility can set its priorities in terms of measurable improvements. At present, a numerical environmental performance per production facility does not exist in the electronics industry, which means that measurable improvements cannot be realized. The numerical environmental performance is linked to the cost structure of the production facility in terms of materials, water and energy use, which means that improvement of the environmental performance results in a cost decrease on the long term. The benefit of environmental performance is that internal improvement actions can be set, which can also be communicated externally in terms of marketing and brand-image improvement. The communication of measurable environmental improvements for each production facility offers new opportunities from a business perspective. When, for instance, environmental performances exist for comparable production facilities, correct environmental benchmarking is also possible from a supply chain management perspective. From a customer's perspective the environmental performances of each suppliers' production facilities can be used from a business perspective too. In practice this can mean a link between environmental performance and the supplier's purchase turnover. This paper views the environmental performance of a production facility from a customer's perspective as the requesting party and from a supplier's perspective as the delivering party. From the scope of a customer–supplier relationship, the existing environmental activities in the electronics industry with respect to environmental management systems, green procurement, design for environment and energy costs are primarily discussed. Secondarily, a new environmental-business model is outlined, which represents the environmental performance of a production facility [1]. Based on this model extended research has been conducted in the worldwide printed board industry, which is shown and discussed. The air emission behaviour and the energy behaviour of 25 printed board production facilities will be discussed in detail, which shows that these behaviours are not measured and so not managed in this industry sector. Management of the production facility's output flows to air, water and soil represents the concept of "cleaner production". The developed model will show that management of these behaviours represents only the undesired output flows of production facilities and not the desired input flows, as incoming materials, energy, water etc. This paper will close with a conclusion and some recommendations for production facilities.

2. The existing situation in production facilities

2.1. Introduction

The notion of environmental quality in general is driven from the environmental concern related to the human ecosphere. The quality of air, soil and water plays an ongoing role, as does the use of resources and energy. Currently, environmental concern is a reality in the society, which also results in attention to the production facilities in electronics industry. Regarding the current production facilities, many different materials are procured and included in the products. Semiconductors, cables, printed boards, housings, capacitors and various types of subassemblies are required to assemble a telecommunication product. This diversity of components is produced in different kinds of production processes. These components are a sum of base materials. The raw materials are procured through a supplier of the supplier. In some cases, like copper, the next chain can be outlined: copper extraction, pure copper production, leadframe production for semiconductor devices and leadframe preparation before use. Several customer–supplier relationships exist in this chain (see Fig. 3). Environmental quality plays a role in each customer–supplier relationship. For example, supplier S_2 is the customer for supplier S_5. The whole supply chain of an Original Equipment Manufacturer (OEM) contains the suppliers' production facilities S_1 through S_{11}, i.e. from raw-material extraction to the produced components. Regard-

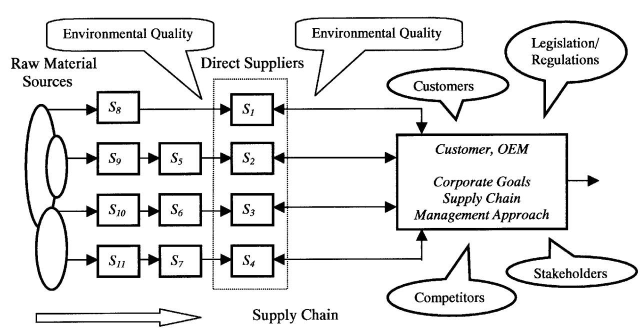

Fig. 3. The supply chain as a sum of customer–relationship.

ing the current supply chain approaches of OEMs, the contacts with the supply chain are limited mostly to the first tier of suppliers, i.e. S_1 to S_4.

The introduction of the concept of environmental quality in the OEM's direct supply chain, S_1 through S_4, shows a large opportunity from an environmental-business perspective for customers and suppliers. This is because the environmental performance of a production facility can be used in terms of marketing from a supplier's perspective and in terms of benchmarking from a customer's perspective. A linkage between the environmental performance of a supplier's production facility and a proposed price reduction related to the customer's purchase turnover is an example of an environmental-business approach. Production facilities S_1 through S_4 generate environmental load in their different production processes, as well as the production facilities deeper in the chain. Each process step in the chain produces solid and liquid waste, air emissions and components, and each process step needs energy, auxiliary compounds, water, raw materials and/or subcomponents. Each produced component can contain environmentally relevant substances or can use too much energy or can be non-recyclable. The introduction of the concept of environmental quality to each customer–supplier relationship in the chain offers an environmental-business opportunity when the suppliers' environmental performances are measured and integrated into the suppliers' negotiations. This paper focuses on the environmental quality of processing methods for components *in* the production facilities in the chain, which has a higher value than the use of environmental management systems and the general terms as environmental performance and green procurement. None of these aspects are linked to the cost structure of production facilities.

2.2. Environmental management systems, ISO14000 series of standards and eco-management and audit scheme (EMAS)

A model of an environmental management system for a production facility is outlined by an International Standardization Organization (ISO) approach (see Fig. 4).

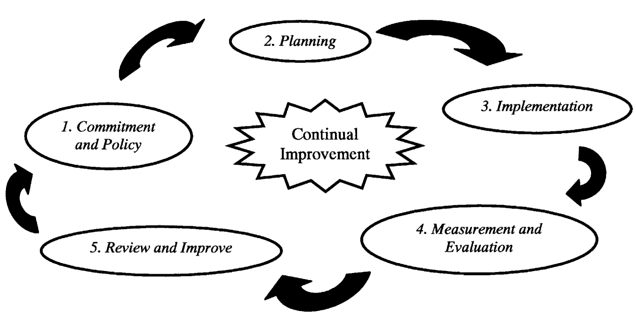

Fig. 4. ISO model of an environmental management system..

The ISO14000 series of standard has been established with respect to environmental management systems. Standards ISO14001 is central to the framework of the ISO14000 series of standard. ISO14001 contains the basic requirements for an environmental management system [2]. When, for instance, senior management of a globally operating semiconductor company decides to introduce an environmental management system in each of its eight waferfabs across the world, the process can be started from the ISO model with the initial principle, *commitment and policy* (Fig. 4). Once initiated, the process can be followed by principles such as *planning*, *implementation*, *measurement and evaluation* and *review and improve*. Based on the ISO approach, the element of continual improvement should be leading.

Following the realization of an environmental management system in each waferfab and by executing the five mentioned ISO principles, the result will be that each waferfab can show its ISO14001 certified environmental management system to customers, governments etc. From an OEM's supply chain management perspective all the suppliers' waferfabs have an ISO14001 certified environmental management system in place, but they are different when compared in depth because terms like environmental performance, environmental impact, continual improvement etc. have been measured, interpreted and implemented in different ways. This emphasizes that when all the suppliers' facilities of an OEM have an environmental management system in place, this does not mean that they have the same *metrics.* This teaches that supplier selection, qualification, ranking and comparison based on an ISO14001 environmental management system does not make sense. Many suppliers' production facilities are currently working towards an environmental management system, which will be certified according to ISO14001. To have such a certified system in place will distinguish them from others, who do not have such a system in place. However, within a period of 5 years each production facility in an OEM's supply chain round the globe will be certified according to ISO14001, from a totally different content of the five principles. This paper describes the *metrics* for determining the environmental performance of comparable production processes of different suppliers from the operational analysis of production facilities. When numerical environmental performances of suppliers' production facilities are available, the fourth step in the ISO model, measurement and evaluation and the concept of continual improvement becomes measurable from a supply chain management perspective. Based on environmental performance suppliers' production facilities can be selected, qualified and benchmarked and the concept of continual improvement becomes valueable.

The eco-management and audit scheme (EMAS) exist alongside the ISO14000 series of standard [3]. The history of the EMAS has been closely linked with that of the ISO14000 standard. This standard will also play a minimum role within the scope of supply chain management. Another aspect, which is not covered by an EMAS or an ISO14001 environmental management system, is the environmental quality of the delivered product. The mass, energy use, environmentally relevant substances, recyclability, recycled content, and quantity of substances of a delivered product, which represents the environmental quality, is not addressed by the five mentioned IS0 principles.

2.3. Environmental performance and green procurement

With respect to environmental performance in the supply chain, Sun Microsystems, Inc. has started to integrate environmental considerations into its supplier management process [4]. The main impetus was to develop a capability to respond to customer inquiries on environmental aspects of the company and its products. Another impetus was the measurement of the use of ozone-depleting substances in the suppliers' product manufacturing processes. These direct impetuses form the basis to adjust the supply chain, but *not from an own supply chain strategy*. These two issues received the greatest attention, but also provided an avenue to initiate a longer-term discussion regarding whether, and how, supplier performance with respect to environmental issues could be addressed. Many ideas are circulating in relation to supply chain aspects, like the development of environmental questionnaires [5,6]. The questionnaires have been focused on obtaining compliance and mostly contain questions relating to the availability of an environmental policy and product design, and nothing more. Examples are:

- Does the facility/corporation have a written environmental policy statement?
- Does the facility have written environmental performance objectives/targets and implementation plans to reduce costs or risks?
- Does your product contain lead?

Furthermore, notions of “green purchasing” and “green procurement” are circulating, but nobody has outlined this in depth and specified the notion of “greenness” related to suppliers [7]. In most cases, green procurement is linked to a large variety of product and process aspects of the supplier. These aspects are: ecolabels, the avoidance of environmentally relevant substances, energy use, use of recycled materials, product mass, re-usability of some parts, recyclability, the use of environmental management systems and the application of Design for Environment (DfE) or Life Cycle Assessment (LCA). Green procurement is embodied by supplier questionnaires related to the aspects mentioned. In practice it means that one or more questions have been defined per aspect. Some questions are open, but others enable the supplier to respond with “yes” or “no”. In general, green procurement can be described as several short-term actions, driven from the OEM to the direct supplier, which are activated by drivers from outside the company, such as customers, competitors, laws, regulations and directives. When an OEM influences its supply chain from the external driver, it shows a defensive supply chain approach, not based on vision, strategy, innovation and leadership of the company. The OEM's green procurement approach is to be compliant with customers, laws and regulations because non-compliance is a threat to the business.

2.4. Environment quality in relation to costs

The production of electrical energy results in the emission of CO_2 and acid compounds such as NO_x and SO_2. A minimization of energy use results in the minimization of CO_2 ejection and a minimization of the greenhouse effect, while minimization of material use results in less dissipation. The supply chain can be divided into printed boards, capacitors, coils etc. The production of these components needs energy, materials and water and produces waste. This shows that the suppliers' production facilities in the chain can be approached from both an environmental and an economic perspective. It also shows that an internal driver can operate alongside the external environmental driver. Within the scope of supply chain management, an internal driver is defined as a driver, which is not triggered by external sources like legislation, customers, competitors or stakeholders, but by supply chain goals such as cost reductions linked to environmental improvements and vice versa. See for instance, the costs of energy use for heat and power by eight selected sectors in the electronics industry in the United States of America (USA) during 1991 in Table 1. The sector original equipment in Table 1 contains computers, computer storage equipment, terminals, peripheral equipment, office machines and calculating and accounting equipment. “Other electronic components”, is a sector that includes crystals, filters, switches, piezoelectric devices, microwave components and printed board assemblies. Table 1 shows the *energy costs of the suppliers* of the OEMs. The sectors, printed boards, semiconductors and original equipment have the highest energy costs. These energy costs influence the selling prices of the components and products. The main part of the energy costs is related to the electrical energy. When the energy costs per produced component are managed, environmental quality is linked to a business perspective.

The *material use in the production facilities* is another element, which can be influenced from a management approach. When, for example, wafer production process

Table 1
Energy costs in the electronics industry in the USA, during 1991

Total supply chain of OEMs		Costs (million $) fuel/electricity energy	Costs (million $) electrical energy	Costs (million $) fuel
1	Printed Boards	126.8	103.8	23
2	Semiconductors	467.3	420.7	46.6
3	Capacitors	33.1	28.7	4.4
4	Resistors	14.8	12.9	1.9
5	Coils and Transformers	10.5	8.6	1.9
6	Connectors	46.8	39.9	6.9
7	Other Electronic Components	186.6	158.6	28
8	Original Equipment	338	304.8	33.2

needs 100 kg silicon per hour and produces 75 kg wafer per hour, what has happened to the 25 kg silicon? When this mass of silicon is scrapped, this means no efficiency with respect to use of resources. An efficient use of material resources is coupled to the cost price and the selling price of a component or material. When the material costs per produced component can be reduced, environmental quality is linked to the business perspective too. The management of the necessary materials per kilogram product produced constitutes an opportunity, along with the necessary quantity of water and auxiliary compounds per kilogram component produced. The use of materials, auxiliary compounds, water, energy and packing materials determines a part of the cost structure of each production facility, as well as the costs for solid and liquid waste handling and for measuring air emissions. Minimizing this use will decrease the environmental load and the cost structure on the long term.

3. Managing the environmental performance of production facilities — an environmental supply chain approach

3.1. Introduction

The management of environmental quality in the supply chain can be driven from its own corporate goals or from customers, competitors and/or legislation. Customers, competitors, stakeholders and legislation are external drivers for a company, while the corporate goals are internal drivers, like realization of cost savings from an environmental perspective. When a customer of an OEM has specific questions relating to the material content of the delivered product, the questions should be answered directly or when, for instance, the use of chromium in products is forbidden in Europe, the OEM should take action immediately. When the OEM carries out activities in compliance with it's customer's request, and complies with the legislation, but does not study the backgrounds of these requests and laws, the OEM puts itself in a reactive position. A reactive mode involves what one has been asked to do and nothing more. The choice for such a mode does not require an own strategy or approach. Independent of customer questions, regulations and laws, but linked to corporate goals, the above major question relating to the material content of products can be the trigger for a company to develop an environmental business strategy. To have in place an own environmental business strategy means to operate from an offensive leading position (see Fig. 5). An environmental supply chain strategy, a product strategy and a marketing strategy can be derived from a company's environmental business strategy. The linkages between costs and environmental impact should be a leading element in these strategies. Because the material content of the OEM's products is mainly determined by the supply chain, it emphasises that a supply chain approach is necessary. The new environmental supply chain approach was developed from the concept of life cycle thinking, with a focus on direct suppliers' production processes.

When the production processes of suppliers are comparable, the environmental load per kilogram produced component is also comparable. For instance, production facility A and B produce comparable printed boards. Production facility A uses 5 kg base materials and production facility B uses 7 kg base materials for 1 kg printed board. Comparison of A and B shows that production facility A has a better environmental performance than production facility B. This also means that

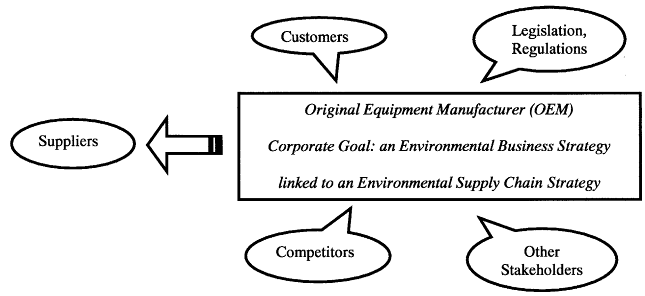

Fig. 5. An environmental supply chain strategy is linked to a corporate goal.

production facility A has lower costs for the base materials and less solid waste. Less solid waste results in less waste handling costs. Production processes in general use materials, auxiliary compounds, water, energy and packing materials to transport the product to the customer, and generate air emissions and solid and liquid waste. These seven environmental load elements determine the environmental performance of a production facility. These environmental load elements form the basis for a management model or Environmental Performance Tool. The generated environmental load of 1 kg component by the use of materials, auxiliary compounds, water, energy and packing materials etc. is inversely proportional to environmental performance, which is general expressed by Eq. (1).

$$E_{\text{P,PRODUCTION FACILTY}} \propto \frac{1}{E_P}. \quad (1)$$

Based on an environmental performance per production facility, facilities can be managed because an environmental performance is a measurable tangible. The management problem is determined by a lack of Environmental Performance Tools. Without the application of Environmental Performance Tools it is impossible to determine the environmental performance of a production facility, which means the internal policy in terms of measurable improvements cannot be executed and the external policy in terms of brand image improvement cannot be communicated. An Environmental Performance Tool for assessments of production facilities should contain two parts:

- A set of specified questions related to the use of materials, auxiliary compounds, water, energy, packing materials, air emissions and waste, the so-called data collection process related to the seven environmental load elements.
- A model, which generates a numerical environmental performance value.

When an environmental performance per production facility is available, facilities can be ranked, classified in terms of good or bad and development from bad to good. Based on environmental performance, a linkage to the supplier's purchase turnover can be made, which results in a proposed price reduction. Environmental quality can only be integrated into the supply chain based on the supplier's environmental performance *and* the linkage to the purchase turnover. Proposed price reductions linked to bad environmental performances trigger suppliers to improve themselves competitively. Without this linkage, the supply chain policy will receive no content from a business perspective.

Supplier or production facility development from an environmental perspective is defined as eco-supplier development or eco-production facility development, which is based on continual improvement. This development suggests two or more different measurable environmental situations of a production facility and the method of changing from environmental situation A to environmental situation B (see Fig. 6). The challenge for the OEM is *how* to activate suppliers in such a way that they initiate innovations in their processes and components from an environmental business perspective, which results in a reduction of the environmental load for the existing chain. The challenge for the production facilities is to determine its environmental performance in a measurable way, to realize measurable improvements and to communicate the improvements in terms of marketing.

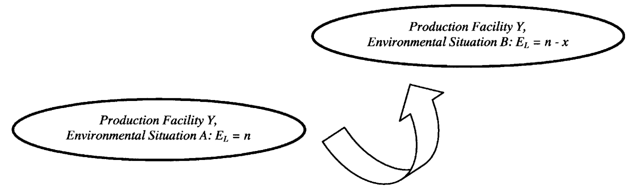

Fig. 6. Eco-supplier or eco-production facility development.

Fig. 6 determines environmental situation A for production facility Y with $E_L=n$, while the environmental load in environmental situation B has been decreased by x until $E_L=n-x$. Eco-supplier development is a core competence in a supply chain policy and creates a supply chain management approach. Eco-supplier development should be integrated into the supplier development cycle, which also exists for elements such as quality etc. The eco-supplier development cycle embodies six steps, see Fig. 7. The first step is the execution of supplier measurements. Environmental performances per supplier can be calculated and compared from these measurements, which activities represent the second and third steps. Based on the environmental performance proposed price reductions relating to the supplier's purchase turnover can be determined and negotiated with the supplier, see fourth step. This linkage puts environmental quality in the scope of a business perspective and results in an

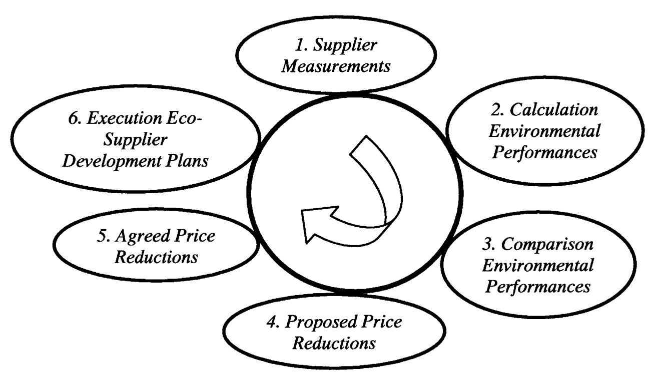

Fig. 7. Eco-supplier or eco-production facility development cycle

agreed price reduction, after negotiation, see fifth step. When the supplier has been classified as very bad and the proposed price reduction is 10% the primary intention is not to cut off the business with the supplier, but to realize an agreed price reduction and on the basis of this to support the supplier with an eco-supplier development plan. Such a plan contains actions for improvement, such as reducing energy consumption by 5% at the same production level, see sixth step. The execution of an eco-supplier development plan is the supplier's responsibility. After, 3 or 4 years, for example, the supplier will be measured again and compared with its competitors. *The essence of the eco-supplier development cycle is to realize environmental improvements by price incentives in the scope of continual improvement.* The activation and continuation of the eco-supplier development cycle cannot take place without Environmental Performance Tools. From the perspective of the production facility the elements of the internal policy are the first, second and sixth step of the eco-production development cycle in Fig. 7. When a production facility measures its production behaviour in terms of material use per kilogram product and decreases the material use per kilogram product the facility can show the environmental improvements in terms of marketing. This attitude does not exist in production facilities, because the quantity of materials is approached from an economic perspective and not from an environmental perspective, while both are connected. The used base materials are not measured in kilograms per unit of time linked to the produced products in kilograms for the same time unit.

3.2. Environmental process modeling based on the relative approach

The contribution to the environmental load of a production process can be approached from the absolute and the relative approach. The absolute approach makes a direct linkage to environmental effects, like ozone depletion, greenhouse effect, smog etc, while the relative approach assumes that a minimum use of materials, water, energy etc. always delivers an environmental benefit. From the relative approach a random production process has five different input flows and three different output flows, see Fig. 8. The five input flows are the quantity of base materials used MB, the quantity of auxiliary compounds used (MH), the volume of water used MW, the amount of energy used (QE), and the quantity of packing materials used (MP). The undesired output flows are air emissions (ME), and the total amount of solid and liquid waste (MWT). The desired output flow is the mass of manufactured products or components (MPC). All these input and output flows are a function of time. These input and output flows are defined as follows:

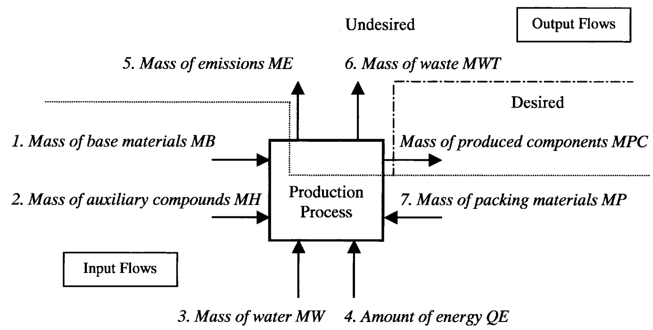

Fig. 8. Environmental balance production process.

1. Input flow of base materials (MB): The desired component is produced from these materials for sale to the customer.
2. Input flow of auxiliary compounds (MH): These chemical compounds are necessary to produce the desired component, but are not included in the component.
3. Input flow of water (MW): Water in combination with chemical compounds is necessary to produce the desired component, but is not included in the component.
4. Input flow of energy (QE): Energy is necessary to produce the desired component.
5. Output flow of air emissions (ME): The production of the desired component generates an undesired flow of air emissions.
6. Output flow of waste (MWT): The production of the desired component generates an undesired liquid and solid waste flow of water, chemical compounds, metals, plastics and paper etc.
7. Input flow of packing materials (MP): These packing materials are used to transport the produced component from the production facility to the customer.

The rate of production depends on the rates of the use of materials, auxiliary compounds, water and energy, while the generated waste and air emissions per unit time are also linked to the production rate. The production rate and its relations to the other flows per unit time can be expressed by seven differential equations [1]. From these equations seven environmental indicators can be derived. With some simplification the following seven environmental indicators can be compiled, (see Eqs. (2)–(8).

$$I_1 = \frac{MPC}{MB} \tag{2}$$

$$I_2 = \frac{MPC}{MH} \tag{3}$$

$$I_3 = \frac{MPC}{MW} \tag{4}$$

$$I_4 = \frac{MPC}{QE} \tag{5}$$

$$I_5 = \frac{MPC}{ME} \quad (6)$$

$$I_6 = \frac{MPC}{MWT} \quad (7)$$

$$I_8 = \frac{MPC}{MP}\,. \quad (8)$$

In these equations the five input and two undesired output flows are linked to the mass of manufactured products or components (MPC). These seven environmental indicators represent the environmental performance of the production facility. The higher the ratios between the produced mass of products or components, MPC, and the number of environmental load elements, the more efficient the production will be. This means in theory, that the environmental indicators I_1 to I_7 will operate between $0 \leq I_1, I_2, I_3, I_4, I_5, I_6, I_7 \leq \infty$. Environmental indicators, I_1, I_2, I_3, I_4 and I_7 are defined as output-input indicators, while I_5 and I_6 are defined as output–output indicators. The environmental output–input indicators describe the relation between the produced output (MPC) and the input flows. The environmental output–output indicators describe the relation between the produced output MPC and the other output flows. In general the management of the output–output indicators, I_5 and I_6, represents the concept of cleaner production. A minimization of the mass of the air emissions (ME) and the mass of solid and liquid waste (MWT) per kilogram produced product fits within the concept of cleaner production as well as the eco-toxicity of the air emissions and the emissions to land and water.

Eco-toxicity ratios per production facility per industry sector relating to water emissions, but also to air and soil emissions, deserve to be investigated further. When the environmental performance of a production facility is expressed by one or more eco-toxicity ratios relating to different waste flows, production facilities can be ranked, compared, classified and developed from a supply chain management perspective. Regarding for example, the wastewater flow of the printed board production facilities, emissions are found of lead, copper, tin, phosphates etc. Comparison of these wastewater flows shows differences in the execution of measurements for the substances. Because local laws and regulations linked to the facilities differ strongly, the execution of measurements on substances also differs strongly. This means that a generic global eco-toxicity ratio related to a wastewater flow of printed board production facilities cannot be determined. Relating to the execution of measurements on substances in the wastewater flow, the facilities exhibit compliance-oriented behaviour, as well as with respect to the execution of measurements on substances emitted into the air. The attitude of the management of production facilities is to be compliant with laws and regulations. The definition, measurement, improvement and marketing of the eco-toxicity ratio in terms of environmental performance is a new opportunity from an environmental-business perspective. In Eqs. (2)–(8) the notion eco-toxicity is not included, because the establishment of the indicators I_1 to I_7 is a first priority for production facilities. Currently, in general only 35% of the printed board production facilities have been determined its mass balance at a correct way, which means that indicators I_1 to I_7 are correct too.

When the measured environmental indicators I_1 to I_7 per production facility are compared with environmental reference indicators I_{1R} to I_{7R}, the 'best practices', the gap between two different environmental situations A and B can be established, see Fig. 6. When in practice the reference indicators I_{1R} to I_{7R} are chosen so that $I_{1R}, I_{2R}, \ldots I_{7R} > I_1, I_2, \ldots I_7$, the ratios x_1 to x_7 between the measured and the reference indicators vary between $0 \leq x_1, x_2, x_3, x_4, x_5, x_6, x_7, \leq 1$. This results in Eq. (9).

$$x_n = \frac{I_n}{I_{nR}} \; for \; n = 1,2,3,4,5,6,7 \; and \; 0 \leq x_n \leq 1 \quad (9)$$

With some mathematics [1] a normalized environmental performance $\|E_{PN}\|$ per production facility can be determined, see eq. (10). When expression (9) has been filled in eq. (10), eq. (11) exists. Here, each measured indicator I_1 to I_7 is compared with its reference indicator I_{1R} to I_7.

$$\|E_{PN}\| = \sqrt{\frac{1}{7}\cdot\{x_1^2 + x_2^2 + x_3^2 + x_4^2 + x_5^2 + x_6^2 + x_7^2\}}. \quad (10)$$

$$\|E_{PN}\| = \sqrt{\frac{1}{7}\cdot\left\{\left[\frac{I_1}{I_{1R}}\right]^2 + \left[\frac{I_2}{I_{2R}}\right]^2 + \left[\frac{I_3}{I_{3R}}\right]^2 + \left[\frac{I_4}{I_{4R}}\right]^2 + \left[\frac{I_5}{I_{5R}}\right]^2 + \left[\frac{I_6}{I_{6R}}\right]^2 + \left[\frac{I_7}{I_{7R}}\right]^2\right\}}. \quad (11)$$

In Eq. (10) each ratio x_n has the same environmental weighting. This means in theory that each ratio x_n is multiplied by 1/7. But in practice it means that the consumption of materials is equal to the consumption of auxiliary compounds, water, energy etc. from an environmental impact perspective. Application of the same environmental weighting indirectly implies application of a quality approach, which means that the consumption of materials, auxiliary compounds, water, energy and packing materials and the generation of air emissions and waste should be equal to the established *perfect* reference indicators I_{1R} to I_{7R}. If $I_1 = I_{1R}$, $I_2 = I_{2R}, \ldots I_7 = I_{7R}$, the $\|E_{PN}\| = 1$, which represents the best performance value. The operating range of the normalized environmental performance is given by Eq. (12). The operating range of $\|E_{PN}\|$ offers a simple solution with respect to production facility classification.

$$0 \leq \|E_{PN}\| \leq 1 \quad (12)$$

The $\|E_{PN}\|$ can be also applied to the supply chain of an OEM. $\|E_{PN}\|$ expresses the environmental performance of a mass of produced components in a production facility during a period of time. When for instance, 25 printed board suppliers are assessed by means of a data collection process for each environmental load element, and the answers provide the information that allow a normalized performance to be determined, the suppliers can be benchmarked and classified in an easy and understandable way. Table 2 contains an example of classification of suppliers' production facilities. If, for instance, the deviation of the assessed supplier, i.e. environmental indicators I_1 to I_7, is less than 10% of the reference indicators, the supplier is classified as E1. This means that $\|E_{PN}\|$ operates between 0.9 and 1. In such a way, each $\|E_{PN}\|$ of a supplier can be redirected to an E-level and classified as good, sufficient, insufficient, bad and very bad.

4. The environmental performance of a printed board production facility linked to its cost structure

An operational analysis of a printed board production facility from an environmental perspective needs data from the following environmental load elements: material use, use of auxiliary compounds, water consumption, energy consumption, ejected air emissions, waste flows and packing materials. The facility's policy relating to these elements is influenced by local and regional environmental regulations and agreements with respect to noise, emissions, wastewater, landfill, nuisance and quality of the soil around the production facility. One of the key figures to be established regarding the flow of procured base materials, such as, laminates, copper foils, copper anodes, lacquers and glass-resin materials, is their percentage in the end product. Using research results, the facility's annual production of the mass of printed boards will be linked to the flow of materials, auxiliary compounds, water and energy use, waste, air emissions and packing material. These seven environmental load elements are used to elaborate an Environmental Performance Tool. Table 3 gives an environmental profile of a mass of produced printed boards in a facility, during 1997. The production and transport of 494 952 kg printed boards needs a mass of materials, auxiliary compounds, water, packing materials and an amount of energy and produces air emissions and solid and liquid waste. The "costs" column shows a distribution of the costs over the seven environmental load elements. The costs with respect to the ejection and filtering of air emissions are unknown, which means that these are included in the overhead costs of the facility. During 1993, emission measurements were executed to obtain a correct view of the emission behaviour of the facility. The costs for these measurements amounted to \$150 000. The "indicators" column gives the ratios between the mass of produced boards and the seven environmental load elements, which shows an application of Eqs. (2)–(8). The final column of Table 3 shows what is needed to produce and pack 1 kg printed board. A specific conclusion linked to good or bad environmental performance cannot be established from this table because it gives an impression of only one production facility. The seven elements identified all affect the environment, as well as the cost structure of the facility. The use of materials, energy, water, auxiliary compounds, packing material and the handling of waste have been linked to the cost price of a printed board. In the period between 1991 and 1998, the price of the process water increased threefold in the area of the facility researched. The price of a kilowatt-hour of electrical energy is also rising slowly. The energy costs (electrical and natural gas) for the manufacturing of 1 kg printed board are \$4.25.

The production facility's cost structure can be divided into four parts: the costs of materials, water, energy etc., labour costs, overhead costs and selling costs. These costs (C) plus the profit (P) determine the turnover (TO) of the production facility. In the case of the production facility, the turnover for 1997 is outlined in Table 4. The costs of materials, auxiliary compounds, water, energy, waste handling and packing materials together are 28.3% of the turnover. A study of the costs of these seven environmental load elements shows that the use of

Table 2
Classification of production facilities in the supply chain

#	Environmental Indicators I_1 to I_7	Classification Production Facilities $\|E_{PN}\|$	E-levels
1	0–10% deviation of I_{1R} to I_{7R}	0.9–1	$0.9<E1\leq1$, good
2	10–20% deviation of I_{1R} to I_{7R}	0.8–0.9	$0.8<E2\leq0.9$, sufficient
3	20–30% deviation of I_{1R} to I_{7R}	0.7–0.8	$0.7<E3\leq0.8$, insufficient
4	30–40% deviation of I_{1R} to I_{7R}	0.6–0.7	$0.6<E4\leq0.7$, bad
5	Larger than 40% deviation of I_{1R} to I_{7R}	0–0.6	$E5\leq0.6$, very bad

Table 3
Environmental profile printed board production facility during 1997

Mass printed boards produced 494 952 kg					The processing of 1 kg printed board requires and generates
Environmental load elements			Costs ($)	Indicators	
1	Mass materials MB	926 815.6 kg	15 066 416	$5.34 \cdot 10^{-1}$	1.87 kg
2	Mass auxiliary compounds MH	9 275 290.2 kg	5 222 408	$5.34 \cdot 10^{-2}$	18.74 kg
3	Mass incoming water flow MW	690 469 000 kg	647 024	$7.168 \cdot 10^{-4}$	1395 kg
4	Energy QE	$185.22 \cdot 10^{12}$ J	2 102 828	$2.6 \cdot 10^{-9}$ kg/J	$3.74 \cdot 10^{8}$ J
5	Mass of air emissions ME	27 969.35 kg	negligible	10.72	93 g
6	Mass of waste flows MWT	$7.62 \cdot 10^{8}$ kg	1 609 100	$6.495 \cdot 10^{-4}$	1539.5 kg
7	Mass packaging materials MP	51 845 kg	69 324	9.55	105 g

Table 4
Description turnover of the production facility during 1997

Turnover printed board production facility				
1. Costs	Materials	$ 15 066 416	61%	28.3%
	Auxiliary compounds	$ 5 222 408	21.1%	
	Water	$ 647 024	2.6%	
	Energy	$ 2 102 828	8.5%	
	Air emissions	Negligible	0%	
	Waste	$ 1 609 100	6.5%	
	Packing materials	$ 69 324	0.3%	
2. Costs	Labour			
3. Costs	Factory overhead			
4. Costs	Selling and administration	$62 482 900		71.7%
5. Profit				
Turnover		$ 87 200 000		100%

materials represents 61% of these costs. The costs for the environmental load element air emissions and packing material are negligible compared with the material and auxiliary compounds costs. In the scope of cost savings, the facility's policy will be to minimize material costs and the costs for auxiliary compounds, followed by energy, waste handling and water. A study of the waste costs shows that the handling of the wastewater flow represents 80% of the costs, while handling the process chemicals and sludge represents 9.8 and 4.7% of the costs respectively. The other 5.5% of the waste costs is determined by the handling of plastics (0.8%), metals (1.9%), paper and cardboard (0.6%), solid printed board materials (2%) and household waste (0.2%). Because the production processes for printed boards are comparable, the distribution of the costs for materials, auxiliary compounds, water etc. will be roughly comparable too. From a cost savings perspective the following four points have the first priority:

- Minimization of base materials
- Minimization of auxiliary compounds
- Minimization of energy use
- Minimization of waste

When the production facility transfers these points to executable actions, which are feasible on the long term, the normalized environmental performance $||E_{PN}||$ is managed and will increase. The execution and monitoring of actions will also give an increase in indicator I_3, because, for instance, a reduction of the wastewater flow of 10% also gives a reduction in incoming water flow. This also means that the waste costs will be reduced. At this moment the management of production facilities does not realize itself that a decrease of material costs and/or energy costs at the same production rate in a certain time frame results in an improvement of the environmental performance.

5. A global application of an environmental performance tool based on the relative approach in the printed board industry

5.1. Introduction

Based on an evaluated and validated Environmental Performance Tool, a global implementation of environmental quality in the OEM's printed board supply chain has been applied from the relative approach. The objective of this implementation step is to establish normalized environmental performances for several printed board suppliers, from an environmental-business perspective. In this scope, 25 suppliers' production facilities, A_1 through A_{25}, were selected for the execution of environmental assessments. These facilities are located in different regions around the globe and produce different kinds of printed boards. Table 5 shows the locations of the production facilities. Most of the production facilities are located in the USA, in total 13. The suppliers' facilities A_8, A_9, A_{10}, A_{14} A_{20}, A_{21} and A_{25} are located in Europe, while A_4, A_{22}, A_{23} and A_{24} are located in Asia. These suppliers' production facilities represent a substantial part of the OEM's purchase turnover.

These 25 suppliers' production facilities were assessed with the aid of the following procedure. Before the start of the supplier assessments, the OEM compiled an overview of appropriate environmental contact persons for each facility. The facilities then received an introductory letter about the environmental activities, research and the OEM's developed supply chain strategy. This letter contained an explanation of the environmental-quality concept from a business perspective. This means in practice that the environmental assessment results are integrated in the business and the facilities will be classified as good, sufficient, insufficient, bad and very bad. The introductory letter also announced that by a certain date, the facility would be receiving a second letter plus a floppy disk containing the environmental survey. The letter was signed by the purchaser, quality engineer, and the environmental expert. Five weeks after the introductory letter, the second letter plus the environmental survey was sent to the suppliers' production facilities. This letter contained the same message as the first one, and was also signed by the same purchaser, quality engineer, and environmental expert. During the 7-week assessment period the environmental expert was available to answer questions and provide support. Most facilities contacted the environmental expert with remarks and questions. Both letters indicated that suppliers' facilities that did not respond to the environmental survey would be classified as very bad after the due date. In both letters, the OEM requested that the facilities send a confirmation to the environmental expert of when they will be able to open the floppy disk containing the survey. During the assessment period, the environmental expert contacted the facilities to inquire about the status of the survey.

This procedure yielded a 100% result as *all* suppliers responded. Supplier A_{13} confirmed that it had received the environmental survey, but far exceeded the due date. Seven weeks after the due date, after receiving several reminders, the President commented that the environmental survey is very comprehensive and that he is open for discussion. Based on the established policy, supplier A_{13} will be classified as very bad, which means the environmental indicators I_1 through I_7 Twill be established as 0, the normalized environmental performance becomes 0 and the proposed price reduction in the negotiations will be 10%. Supplier A_{22} exhibited comparable behaviour. Two days before the due date, they requested the environmental expert to extend the assessment period by 1 week because they intended to provide the correct response. More than 1 week after the new due date, supplier A_{22} delivered a poor result and promised to deliver more answers. The promised answers were still not available 2 weeks later. A final reminder was sent to supplier A_{22}, who did not respond. Supplier A_{22} will also be classified as very bad and the proposed price reduction will also be 10%. Neither suppliers exhibit supportive behaviour.

The other suppliers did respond to the questions of the survey. All the answers relate to production in 1999. A study of the answers identifies inconsistencies in delivered supplier data. This means that some answers are not given or are unreliable. Different answers contradict each other in some cases. Another aspect is that some suppliers did not read the explanation of the survey carefully. The mass balance provides insight into the suppliers' self-management behaviour. The mass balance per supplier, outlined in Section 5.2, exhibits an initial impression of the inconsistency. Independent of the inconsistency, the answers delivered relate to use of materials, auxiliary compounds, water, energy and packing materials and were used to calculate input–output indicators I_1, I_2, I_3, I_4 and I_7 for each facility. The answers delivered relate to the generated air emissions and solid and liquid waste were used to calculate output–output indicators I_5 and I_6. Sections 5.3 and 5.4 discuss the sample size of the 25 suppliers' production facilities for the environmental load elements energy use (I_4) and air emissions (I_5). This means that the energy use and the air emission behaviour in the sample size will be discussed in detail, and the highest or best indicator will be selected. Based on the selected indicators or reference indicators, the normalized environmental performance

Table 5
Distribution of suppliers' production facilities per region

Supplier A_1	USA	Supplier A_6	USA	Supplier A_{11}	USA	Supplier A_{16}	USA	Supplier A_{21}	Europe
Supplier A_2	USA	Supplier A_7	Canada	Supplier A_{12}	USA	Supplier A_{17}	USA	Supplier A_{22}	Asia
Supplier A_3	USA	Supplier A_8	Europe	Supplier A_{13}	USA	Supplier A_{18}	USA	Supplier A_{23}	Asia
Supplier A_4	Asia	Supplier A_9	Europe	Supplier A_{14}	Europe	Supplier A_{19}	USA	Supplier A_{24}	Asia
Supplier A_5	USA	Supplier A_{10}	Europe	Supplier A_{15}	USA	Supplier A_{20}	Europe	Supplier A_{25}	Europe

per supplier's production facility was determined and a proposed price reduction was derived, see Section 5.5. This result shows an initial environmental quality implementation step in the supply chain, which can be followed by communication to the supplier, the development of eco-supplier development plans, including in existing supplier profiles etc., see Fig. 7.

5.2. Discussion of mass balances in the sample size

In theory, a mass balance is in balance when the sum of the input flows (materials, auxiliary compounds, water and packing materials), is equal to the sum of the output flows (air emissions, waste and produced printed boards). The mass balance per production facility has been determined on the basis of the delivered supplier data, which offers a management control. Table 6 shows an overview of the mass balances of the assessed suppliers relating to the production of 1 kg printed board. The sum of the input flows minus the sum of the output flows should be 0. Regarding the mass balance of supplier Al, the sum of the inputs is 756.4 kg, while the sum of the outputs is 491.28 kg. The difference between the sum of the inputs and that of the outputs is 35.1%, because the sum of the inputs is *greater* than the sum of the outputs. Because 95–98% of the generated waste is wastewater, the water intake is not comparable to the wastewater flow. From this difference it can be concluded that supplier A_1 has a weak overview of its mass balance. Regarding the mass balance of supplier A_{10}, the sum of the input flows is 1016.78 kg, while the sum of the output flows is 1318.63 kg. This means that the sum of the input flows is 22.9% *smaller* than the sum of the output flows, which is impossible from a physical viewpoint. In Table 6 when the sum of the input flows is greater than the sum of the output flows, the difference is shown by a plus sign, while a minus sign indicates that the sum of the input flows is smaller than the sum of the output flows. A study of the differences between the sum of input flows and the sum of output flows shows that most suppliers have no real insight into their mass balance. When a measure of inaccuracy is accepted within the range of -15 to +15%, only suppliers A_5, A_6, A_8, A_{11}, A_{12}, A_{14}, A_{15}, A_{16} and A_{19} have insight into their mass balance. If this is representative for the industry, only a third knows what its mass balance is.

5.3. Discussion of energy use and selection of indicator I_4

Table 7 shows the use of energy in the sample size of the assessed suppliers. The ratio (MPC/QE) and hence

Table 6
Mass balances of the 25 assessed printed board suppliers

#	Input Flows					Output Flows				Difference
	MB (kg)	MH (kg)	MW (kg)	MP (g)	$\sum$inputs (kg)	ME (g)	MWT (kg)	MPC (kg)	$\sum$outputs (kg)	Δ(%)
Supplier A_1	12.11	3.45	740.74	100	756.4	78.86	490.2	1	491.28	+35.1
Supplier A_2	7.78	4.94	473.93	175.44	486.83	12.38	396.83	1	397.84	+18.3
Supplier A_3	7.07	3.35	854.7	123.46	865.24	34.05	396.83	1	629.96	+27.2
Supplier A_4	1.97	9.29	1694.92	95.6	1706.28	44.44	1312.34	1	1313.38	+23
Supplier A_5	6.99	3.96	370.37	104.17	381.4	24.42	384.62	1	385.64	−1.1
Supplier A_6	1.74	6.73	970.87	98.91	979.44	154.56	869.57	1	870.72	+11.1
Supplier A_7	1.58	3.84	641.03	37.95	646.49	57.93	442.48	1	443.54	+31.4
Supplier A_8	1.67	14.49	1052.63	39.42	1068.83	34.49	1124.86	1	1125.89	−5.1
Supplier A_9	1.57	10.75	684.93	487.8	697.74	5.38	588.24	1	589.25	+15.5
Supplier A_{10}	5.18	10.99	1000	609.76	1016.78	112.49	1317.52	1	1318.63	−22.9
Supplier A_{11}	7.76	100	7142.86	52.63	7250.67	246.91	7042.25	1	7043.5	+2.9
Supplier A_{12}	1.47	1.34	273.97	43.1	276.82	30.67	275.48	1	276.51	+0.1
Supplier A_{13}	–	–	–	–	–	–	–	–	–	–
Supplier A_{14}	1.35	3.27	330.03	56.21	334.71	68.07	289.02	1	290.09	+13.3
Supplier A_{15}	2.02	3.31	588.24	33.9	593.6	27.12	588.24	1	589.27	+0.7
Supplier A_{16}	1.55	3.67	680.27	74.35	685.56	0.0259	704.23	1	705.26	−2.8
Supplier A_{17}	1.86	1.81	421.94	19.83	425.63	24.13	4166.66	1	4167.68	−89.8
Supplier A_{18}	2.35	2.63	416.66	19.83	421.63	20.47	267.38	1	268.4	+36.3
Supplier A_{19}	1.73	6.78	769.23	69.25	777.81	49.75	793.65	1	794.7	−2.1
Supplier A_{20}	1.69	8.82	380.23	86.96	390.83	30.44	584.8	1	585.83	−33.3
Supplier A_{21}	0.99	4.87	0.26	50	6.17	–	3.64	1	4.64	+24.8
Supplier A_{22}	–	–	–	–	–	–	–	–	–	–
Supplier A_{23}	1.63	2.61	227.79	10	232.04	0.047	119.05	1	120.08	+48.3
Supplier A_{24}	1.81	4.98	1492.54	94.07	1499.42	50.68	1190.48	1	1191.53	+20.5
Supplier A_{25}	0.68	1.49	0	41.67	2.21	0.0059	106.95	1	108	−98

Table 7
Overview of ratios and indicators relating to energy use and air emissions

#	[MPC/QE]	1 kg printed board needs:(J)	I_4 (-10^{-9})	[MPC/ME]	Air emissions generated per kg printed board	I_5
Supplier A_1	$3.93\cdot10^{-9}$	$2.54\cdot10^{8}$	3.93	12.68	78.86 g	12.68
Supplier A_2	$8.06\cdot10^{-9}$	$1.24\cdot10^{8}$	8.06	80.75	12.38 g	0
Supplier A_3	$5.59\cdot10^{-9}$	$1.79\cdot10^{8}$	5.59	29.37	34.05 g	29.37
Supplier A_4	$3.54\cdot10^{-9}$	$2.82\cdot10^{8}$	3.54	22.5	44.44 g	22.5
Supplier A_5	$5.78\cdot10^{-9}$	$1.73\cdot10^{8}$	5.78	40.95	24.42 g	40.95
Supplier A_6	$2.78\cdot10^{-9}$	$3.6\cdot10^{8}$	2.78	6.47	154.56 g	6.47
Supplier A_7	$6.5\cdot10^{-9}$	$1.54\cdot10^{8}$	6.5	17.26	57.93 g	17.26
Supplier A_8	$3.33\cdot10^{-9}$	$3\ 10^{8}$	3.33	28.99	34.49 g	28.99
Supplier A_9	$3.31\cdot10^{-9}$	$3.02\cdot10^{8}$	3.31	186	5.38 g	0
Supplier A_{10}	$5.27\cdot10^{-9}$	$1.9\cdot10^{8}$	5.27	8.89	112.49 g	8.89
Supplier A_{11}	$1.02\cdot10^{-9}$	$9.8\cdot10^{8}$	1.02	4.05	246.91 g	4.05
Supplier A_{12}	$6.11\cdot10^{-9}$	$1.64\cdot10^{8}$	6.11	32.6	30.67 g	32.6
Supplier A_{13}	–	–	0	–	–	0
Supplier A_{14}	$5.06\cdot10^{-9}$	$1.96\cdot10^{8}$	5.06	14.69	68.07 g	14.69
Supplier A_{15}	$6.11\cdot10^{-9}$	$1.64\cdot10^{8}$	6.11	36.87	27.12 g	36.87
Supplier A_{16}	$1.81\cdot10^{-9}$	$5.52\cdot10^{8}$	1.81	38511.7	25.97 g	0
Supplier A_{17}	$4.32\cdot10^{-9}$	$2.31\cdot10^{8}$	4.32	41.45	24.13 g	41.45
Supplier A_{18}	$0.6\cdot10^{-9}$	$16.66\cdot10^{8}$	0.6	48.84	20.47 g	48.84
Supplier A_{19}	$7.78\cdot10^{-9}$	$1.29\cdot10^{8}$	7.78	20.1	49.75 g	20.1
Supplier A_{20}	$12.1\cdot10^{-9}$	$0.83\cdot10^{8}$	12.1	32.85	30.44 g	0
Supplier A_{21}	$8.66\cdot10^{-9}$	$1.15\cdot10^{8}$	8.66	–	–	0
Supplier A_{22}	–	–	0	–	–	0
Supplier A_{23}	$400\cdot10^{-9}$	$2.5\cdot10^{6}$	0	28811.67	34.71 mg	0
Supplier A_{24}	$1.6\cdot10^{-9}$	$6.25\cdot10^{8}$	1.6	19.73	50.68 g	19.73
Supplier A_{25}	$25.9\cdot10^{-9}$	$38.6\cdot10^{6}$	0	168000	5.95 mg	0

the indicator I_4 was calculated on the basis of the delivered data of the suppliers. For these calculations Eq. (5) has been used. A study of Table 7 shows great diversity in the ratio (MPC/QE). In general, suppliers A_{18} and A_{20} represent the operating range of ratio (MPC/QE), which varies between $0.6\cdot10^{-9}$ and $12.1\cdot10^{-9}$. Suppliers A_{23} and A_{25} exhibit ratios that do not seem realistic. Supplier A_{23} uses a factor of 33 less energy than supplier A_{20}. Such a ratio should be established as an inconsistency, because the process equipment in the facilities is comparable. Such an inconsistency should result in an indicator I_4 of 0. Supplier A_{25} uses a factor 2.1 less energy than supplier A20. The gap between the ratios of the suppliers A_{20} and A_{25} is too large to suggest that supplier A_{25} delivers the reference indicator for the sample size. Regarding the answers to the questions for determining indicators I_1, I_2 and I_3 of supplier A_{25}, there are inaccuracies and negligences. This should also result in an indicator I_4 of 0. Summarizing the situation for the sample size, supplier A_{20} delivers the highest indicator I_4, which results in the reference indicator I_{4R}.

5.4. *Discussion of air emissions and selection of indicator I_5*

Table 7 also outlines the air emissions of the suppliers assessed in the sample. The ratio (MPC/ME) has been calculated on the basis of the data provided by the suppliers. Eq. (6) was used for these calculations. Regarding the sample size, most suppliers have not executed concentration measurements in their stacks on the roofs of their production facilities, relating to the combinations of substances. This means that the toxicity ratios cannot be established. Only suppliers A_4, A_7, A_{11}, A_{12}, A_{14}, A_{17} and A_{23} reported any measurement results of concentration of substances. However, a comparison of the measured concentrations identifies wide differences. Regarding the ejection of copper compounds, supplier A_7 reports different measured concentrations, the lowest being 0.001 mg/cm^3, while supplier A_{12} reports that the concentration is less than 0.1 mg/cm^3. Supplier A_{12} indicates a concentration of 0, while supplier A_{23} states that it is not applicable. In the case of the ejection of SO_x and NO_x compounds, supplier A_{17} has not measured this, while supplier A_{23} measured 0.0005 mg/cm^3 as the lowest concentration of SO_x. Based on a study of the measured concentrations, it should be concluded that the toxicity ratio cannot be determined using the supplier data as provided.

The ratios (MPC/ME) in Table 7 also show a great deal of diversity. Supplier A_2 exhibits a fairly high ratio of 80.75, which reflects the ejection of only 12.38 g per produced kilogram printed board. A study of the ejection of the different combinations of substances results in question marks with respect to the NO_x compounds and the volatile organic compounds. These values are 10 000 and 8000 kg per year only and are too exact. It would appear that the estimates are weak and not based on measurements. Furthermore, six kinds of combinations of substances have been marked as not applicable, which is unrealistic in today's printed board industry. This emission behaviour should result in an indicator for I_5 of 0. Supplier A_9 also has a fairly high ratio (MPC/ME). The ejection is only 5.38 g per kilogram produced printed board. Analyzing the ejection of different kinds of combinations shows that five categories have been marked as negligible and six categories as not applicable. This means that the ratio (MPC/ME) is based only on the ejection of chlorine, copper and nickel compounds, and a quantity of volatile organic compounds. Such a weak emission behaviour should also result in an indicator for I_5 of 0.

The ratio (MPC/ME) of supplier A_{16} exhibits a value that appears unrealistic. During 1999, this production facility ejected 0.12 kg formaldehyde into the atmosphere, together with 0.81 kg ammonia compounds, 0.02 kg chlorine compounds, 0.21 kg phosphorous compounds, 0.52 kg SO_x compounds, 0.1 kg NO_x compounds and 6.23 kg volatile organic compounds. This together amounts to an ejection of 8.01 kg caused by the production of 308 479 kg printed boards. This ratio cannot be represented by an indicator because such a "zero-emission facility" does not exist in the current electronics industry. This means that indicator I_5 is established as 0. Supplier A_{20} has a ratio (MPC/ME), which is based solely on a mass of ejected volatile organic compounds and not on other substances. This would appear to be unrealistic, and the ratio cannot be transferred to an indicator I_5. In this case, I_5 has been established as 0. The emission behaviour of supplier A_{21} is unknown because the supplier does not provide any data. Suppliers A_{23} and A_{25} exhibit emission profiles that are similar to supplier A_{16}, which also results in indicators of 0. Regarding indicator I_5 in , nine suppliers have an indicator of 0. Many suppliers have poor insight into their emission behaviour and have made estimations from a customer perspective, thereby generating unrealistic ratios (MPC/ME). In the sample size, supplier Ala delivers the highest indicator, followed by A_{17} and A_5. In this case supplier A_{18} will deliver the reference indicator I_{5R}.

5.5. Discussion of normalized environmental performances in the sample size

In the previous Sections 5.3 and 5.4 the indicators I_4 and I_5 of the assessed suppliers have been discussed and reference indicators I_{4R} to I_{5R} have been selected from the sample size. Based on seven reference indicators, a normalized environmental performance $\|E_{PN}\|$per supplier's production facility has been calculated. With Eq. (11), the indicators I_1 to I_7 and the reference indicators I_{1R} to I_{7R}, the calculated $\|E_{PN}\|$ per supplier is shown in . These selected reference indicators are [1]:

- I_{1R}=60.19·10^{-2} — from supplier A_{16}
- I_{2R}=45.87·10^{-2} — from supplier A_{25}
- I_{3R}=4.39·10^{-4} — from supplier A_{23}
- I_{4R}=12.1·10^{-9} — from supplier A_{20}
- I_{5R}=48.84 — from supplier A_{18}
- I_{6R}=1.87·10^{-3} — from supplier A_{18}
- I_{7R}=24 — from supplier A_{25}

Based on the set of reference indicators, which have been provided by five different suppliers, the calculated normalized environmental performances vary between 0 and 0.66. Supplier A_{12} has the highest performance, followed by suppliers A_{18} and A_{17}. The other suppliers have performances that vary between 0 and 0.53. Within this range, suppliers A_{11}, A_{13} and A_{22} have the lowest performances, while supplier A_{25} has the highest. But all these suppliers exhibit more than 40% deviation from the reference indicators. When the suppliers are ranked, as shown in Table 2, all suppliers with exception of A_{12}, A_{17} and A_{18} are classified as very bad, i.e. level E5. Suppliers A_{12}, A_{17} and A_{18} exhibit 34, 38 and 36% deviation from the reference indicators respectively, which means a classification of bad, i.e. level E4. None of the suppliers can be classified as sufficient or good. These performances determine "environmental situation A" of the supply base, (see for instance Fig. 6).

In the negotiations between an OEM and its suppliers, the elements component quality and reliability, technology, service, delivery performance and price have a role to play in establishing contracts. An unacceptable delivery performance of the supplier impacts the price of components, as well as an unacceptable quality level. The link between environmental quality and price for a number of components or subassemblies can be formalized by a link between the normalized environmental performance of the supplier's production facility and the purchase turnover, which represents the number of components delivered by that facility. The normalized environmental performances, $\|E_{PN}\|$, can operate as a discriminator in the contracting processes. Based on performance, a price reduction (PPR) linked to purchase turnover per supplier's facility (PT_s) can be proposed. In this case, the rule of thumb expressed by Eq. (13) can be used.

$$PPR = [(1-|E_{PN}|)/10]\cdot PT_S. \qquad (13)$$

The result is that the supplier with the lowest performance receives the highest proposed price reduction of purchase turnover per supplier's facility (PT_s), see suppliers A_{10}, A_{11}, A_{13} and A_{22}. *From a business perspective the five suppliers' facilities, which can deliver the highest cost savings should have the first attention in the scope of the eco-supplier development cycle*, *see* Fig. 7.

After an agreed price reduction with the supplier, a required “environmental situation B” can be established and eco-supplier development plans can be developed.

The last column of Table 8 shows the “quality” of the mass balance of the assessed suppliers. As discussed in Section 5.2, only suppliers A_5, A_6, A_8, A_{11}, A_{12}, A_{14}, A_{15}, A_{16} and A_{19} have a correct mass balance. The other suppliers have an incorrect mass balance. In this case normalized environmental performances have been calculated independent of the mass balance, which does not imply that an unbalanced mass balance delivers a low normalized environmental performance or vice versa, see suppliers A_{11} and A_{17}. The weakness of this approach is that suppliers with an unbalanced mass balance can have a relative high performance with respect to sample size, see supplier A_{25}. The strength of this approach is that the performance is calculated based on current best available data, which can be used in supplier negotiations.

6. Conclusion

This paper has shown that environmental quality can be integrated into the existing supply chain of an OEM by using an Environmental Performance Tool. Application of this Environmental Performance Tool has shown that suppliers can be ranked, classified and compared on the basis of their environmental performance and that proposed price reductions can be derived and used in the supplier negotiations. It also shows, however, that only nine of the 25 assessed printed board facilities know what their mass balance is. Therefore, the added strength of this Environmental Performance Tool is that the accuracy of the supplier data can be checked. In this case, the environmental indicators and the normalized environmental performance were calculated independent of inaccuracies in supplier data. Inaccuracies in the data are not a reason for not calculating the environmental indicators and the normalized environmental performance. Inaccuracies in data will be eliminated when the eco-supplier development cycle is activated and continued, (see Fig. 6). In the future, the business impact in terms of proposed price reductions can be expanded widely when suppliers deliver inaccurate data. In this case, it means that 16 printed board facilities have no insight into their mass balance, which should result in a normalized environmental performance of 0, a proposed price reduction of 10% and the classification ‘very bad’. The normalized environmental performances can be calculated and compared for the other nine printed board facilities, and proposed price reductions can be derived.

Based on the statement that only nine of the 25 assessed printed board production facilities know what their mass balance is, it should be concluded that the management of the mass balance is almost non-existent in the production facilities. When the mass balance and the energy use have been determined and combined, a

Table 8
Calculated normalized environmental performances of assessed suppliers

#	$\|E_{PN}\|$	Proposed price reduction PPR	Classification	Region	Difference Δ(%)
Supplier A_1	0.3	7% of PT_s	E5: very bad	USA	+35.1
Supplier A_2	0.41	5.9% of PT_s	E5: very bad	USA	+18.3
Supplier A_3	0.39	6.1% of PT_s	E5: very bad	USA	+27.2
Supplier A_4	0.29	7.1% of PT_s	E5: very bad	Asia	+23
Supplier A_5	0.49	5.1% of PT_s	E5: very bad	USA	−1.1
Supplier A_6	0.24	7.6% of PT_s	E5: very bad	USA	+11.1
Supplier A_7	0.35	6.5% of PT_s	E5: very bad	Canada	+31.4
Supplier A_8	0.32	6.8% of PT_s	E5: very bad	Europe	−5.1
Supplier A_9	0.23	7.7% of PT_s	E5: very bad	Europe	+15.5
Supplier A_{10}	0.2	8% of PT_s	E5: very bad	Europe	−22.9
Supplier A_{11}	0.07	9.3% of PT_s	E5: very bad	USA	+2.9
Supplier A_{12}	0.66	3.4% of PT_s	E4: bad	USA	+0.1
Supplier A_{13}	0	10% of PT_s	E5: very bad	USA	-
Supplier A_{14}	0.41	5.9% of PT_s	E5: very bad	Europe	+13.3
Supplier A_{15}	0.46	5.4% of PT_s	E5: very bad	USA	+0.7
Supplier A_{16}	0.43	5.7% of PT_s	E5: very bad	USA	−2.8
Supplier A_{17}	0.62	3.8% of PT_s	E4: bad	USA	−89.8
Supplier A_{18}	0.64	3.6% of PT_s	E4: bad	USA	+36.3
Supplier A_{19}	0.4	6% of PT_s	E5: very bad	USA	−2.1
Supplier A_{20}	0.46	5.4% of PT_s	E5: very bad	Europe	−33.3
Supplier A_{21}	0.34	6.6% of PT_s	E5: very bad	Europe	+24.8
Supplier A_{22}	0	10% of PT_s	E5: very bad	Asia	-
Supplier A_{23}	0.38	6.2% of PT_s	E5: very bad	Asia	+48.3
Supplier A_{22}	0.37	6.3% of PT_s	E5: very bad	Asia	+20.5
Supplier A_{22}	0.53	4.7% of PT_s	E5: very bad	Europe	−98

total environmental profile of a production facility exists, which can be expressed by environmental indicators I_1 to I_7. The compilation of such a profile is a first necessary step in the scope of the production facility's environmental performance. A second step is the connection to the production facility's cost structure. When indicators I_1 to I_7 exist, feasible objectives can be established, such as a minimization of 3% of the auxiliary compounds and base materials at a same production level. In practice this means an improvement of indicators I_1 and I_2. The third step is the determination of the notion eco-toxicity with respect to air, solid and water emissions, which requires more attention from a research perspective. The data for the compilation of indicators I_1 to I_7 is available in each production facility, but have never been brought together or connected to cost structure. The compilation of indicators I_1 to I_7 demands an integrated approach from the management of the production facility. In practice this means for example, that the establishment of the used base materials and waste in kilogram per year should be integrated into the employee's materials management and waste handling tasks. At present many waste-handling activities of production facilities are approached from a legal perspective, which activates the facilities, but also drives them into a re-active mode. A change from a re-active mode to a pro-active mode means in general that the environmental performance of a production facility can be used as a business opportunity in terms of "we produce more with less". This deserves to be investigated further.

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