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Development of a sustainable product lifecycle in manufacturing firms: a case study

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This study discusses a methodology for integrating Design for Environment (DfE) and life cycle assessment (LCA) techniques both into new product development and into the process of redesigning a set of existing products. The article explains the reasons for developing DfE in general, and pays particular attention to a specific, chosen product, a class of electrical distribution boards, to illustrate the concept. The main process steps in the development of the DfE are outlined, and the development of a LCA that satisfies the requirements of the ISO 14040 standard is illustrated. A major benefit of the DfE methodology proposed in this work is the possibility to use LCA data both during new product development and when modifying old products, with the aim of continuously reducing the overall environmental impact of products during their life cycle. This improvement cycle begins with the attempt to find new design solutions (for assembly and set-up in the case of electrical distribution boards), continues with the calculation of the enviromental break even point (BEP) and with the assessment of the BEP for the expenses incurred by the client. On the basis of these calculations and bearing in mind the technical specifications required by the clients and the work environment in which the product will be used, the designers will be able to make the most efficient choices from both the environmental and the economic point of view.

Keywords: Design for Environment (DfE); Life cycle assessment (LCA); Sustainable product lifecycle; Environmental break even point; Economic break even point

1. Introduction

The growing interest in 'sustainable development' has led many companies to examine the ways in which they deal with environmental issues (Glazebrook *et al.* 2000). To achieve sustainable industry, environmentally conscious design (eco-design) or Design for Environment (DfE) is becoming an increasingly important topic (Brezet and Van Hemel 1997). The introduction of DfE methodologies in manufacturing firms allows attention to be paid to environmental aspects right from

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the start of the design stage leading to a reduction in the materials used and the waste products, avoiding any future weaknesses and inefficiencies.

DfE bears in mind the potential environmental impact throughout the life cycle of the product: emission of harmful substances, excessive use of energy or non-renewable energy sources. It also considers the life cycle of the materials from extraction to disposal. In this way the designers do not create just a product but a whole life cycle. In the practice of eco-design, life cycle assessment (LCA) provides the basic modelling framework for evaluating the environmental load and impact throughout the entire product life cycle from material acquisition to disposal (Wenzel *et al.* 1997).

According to Khan *et al.* (2002) LCA is one of the most important techniques for the successful implementation of a process or product development in the context of environmental sustainability. As Allen (1996) indicated, one of the most common uses of LCA is identifying critical areas in which the environmental performance of the product can be improved.

The use of DfE is also proof of a sense of responsibility towards the consumer and may improve the market position of the firm. Many firms have decided to develop DfE for different core products for several reasons, the main one being that customers are increasingly asking for information concerning the environmental performance of products. This is due to growing environmental awareness and the desire to compare products of different types and from different companies in an environmental context. The development and presentation of environmental product declarations (EPDs) based on the *ISO-TR 14025—Environmental Labels and Declaration: Type III Environmental Declarations* (ISO 2000)—is a logical way of achieving this (Allander 2001). The information incorporated in each EPD is based on LCAs, according to the *ISO 14040—Environmental Management—Life Cycle assessment— Principles and Framework (ISO 1997)*. The resulting EPDs can also serve as good sales arguments for environmentally friendly products.

This work was developed thanks to the collaboration between the Sustainability Affairs Department of ABB Italia and the Department of Energy Studies of Marche Polytechnic University, Ancona, and concerned the design of low tension electrical distribution boards carried out at the ABB SACE SpA factory in Frosinone, Italy. The aim of this study was to create a procedure based on the integration of DfE and LCA methodologies to allow the assessment of improvement, in terms of environmental and economic impact, which could be attributed to a different assembly layout for the 'electrical distribution boards' set of products. The procedure proposed is general and can also be applied to other products and to other industrial realities.

The paper is organized as follows: section 2 describes the methodology necessary for integrating DfE methodologies and LCA techniques into the manufacturing firm. In section 2.1 related research work is discussed and in section 2.2, the procedure for developing a sustainable product lifecycle is presented. Section 3 contains details of a case study for an industry that manufactures electrical distribution boards. In section 3.1 the approach and parameters used in the LCA study are presented. Section 3.2 contains a case study of a specific product used to illustrate the application of the proposed method. Finally, a discussion and some conclusions are presented in section 4.

2. Material and methods

The methodology proposed in this study, illustrated in figure 1, involves the integration of DfE and LCA techniques into those processes which are normally carried out when developing a new product:

- Determination of product function and goals.
- Conceptual design.
- Prototype assembly testing.
- Detailed final design.

The importance of eco-design in earlier phases has been emphasized, because decisions made in these phases greatly affect the environmental impact throughout the product life cycle (Frei and Züst 1997). First of all a manufacturer must examine the context in which the DfE is to be developed. He must identify the important and possible environmental goals within the process and fix the market objective that he wants to reach, whether it is local, national or international. For example, prior to the introduction of legislation he may consider using this technique to arrive at the standards of eco-management contained in ISO 14000. He must assign responsibilities within the firm and must ensure that the process is controllable and traceable. He must involve the entire firm, in particular the managerial staff, indicating DfE as a factor for improvement and market achievement. At the same time he must create awareness (for example by organizing seminars) in all the parties involved in the production process.

The methodology proposed in this study is a closed feedback cycle which is able to improve itself: this is based on a scheduled report system which indicates to the environmental management the need to change some characteristics of the product or the production processes or to address their study towards new products.

The means by which this concept can be integrated into the company is through its DfE program. The DfE tool considered in this paper is a methodological

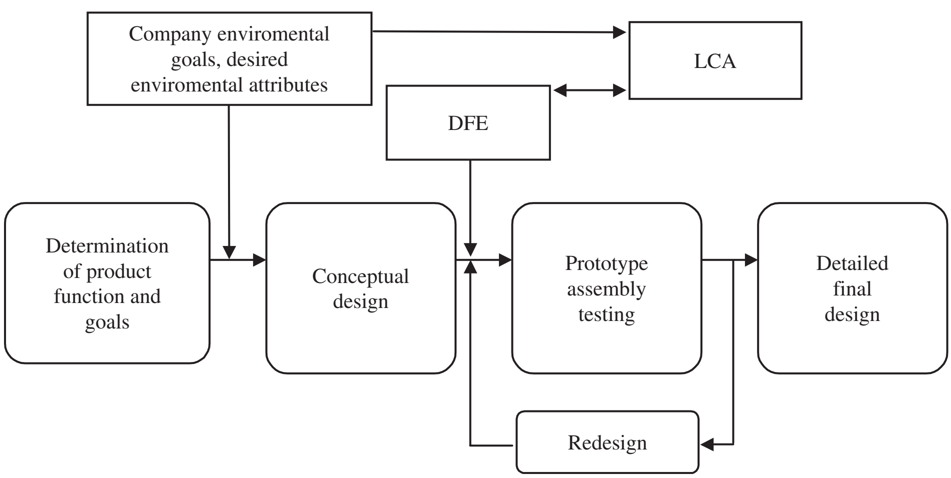

Figure 1. Class product design.

framework based on LCA thinking, which allows the integration of environmental parameters directly into the design of products and processes. DfE serves therefore as an environmental decision-making support for designers. In the design phase of a product the different problems and solutions should be assessed from a technical, economic and ecological point of view at the same time.

2.1 *Related research work*

Many researchers have developed tools for integrating environmental aspects into the product development process (Simon *et al.* 1998). Although there are quite a lot of DfE tools developed by academia and industry, few have made a significant breakthrough so far. According to McAloone (2000), not much effort has been made to understand how these methods can be integrated into the design process (Backmar 2000). Lenox and Ehrenfeld (1995) state that many tool developers fail to consider the organizational context in which tools are to be embedded. Glazebrook *et al.* (2000) showed how different DfE approaches fall short with respect to the requirements of a product design team.

Several authors have proposed an approach of DfE, including cost aspects and LCA. Warburg *et al.* (2001) used the method of life cycle costing (LCC) to implement economic aspects in industrial decision making. Senthil *et al.* (2003) developed a life cycle environmental cost analysis (LCECA) incorporating costing into LCA practice. This model prescribes a life cycle environmental cost model to estimate and correlate the effects of these costs in all the life cycle stages of the product. The newly developed categories of eco-costs are: costs of effluent treatment/control/disposal, environmental management systems, eco-taxes, rehabilitation, energy and savings of recycling and reuse strategies. The mathematical model of LCECA determines quantitative expressions between the total cost of products and the various eco-costs. On the other hand, a method that evaluates an eco-product from the cost and environmental aspects independently has been reported (Biswas *et al.* 1997). In addition, a methodology based on the formulation of compromise decision support problems has been reported (Coulter and Bras 1999). Lye *et al.* (2001) proposed a methodology that scores the cost, quality and environmental standing of four stages of the life cycle of a product. A self-learning algorithm is discussed that computes the best and worst values of the indices from a variety of similar products. However, this method requires a great amount of detailed information, making it inapplicable to the early phases of design.

Many authors have used a quality function deployment (QFD) technique to integrate DfE and LCA methods. Cristofari *et al.* (1996) proposed a new methodology using QFD and LCA to document technical requirements. Hanssen *et al.* (1996) and Ferde *et al.* (1995) applied QFD, LCA and LCC separately for environmentally sound light fittings, but did not form a systematic methodology that could integrate QFD, LCA and LCC into an efficient tool. Zhang *et al.* (1999) proposed a new methodology by integrating LCA, LCC, and QFD into an efficient tool that deploys customer, environmental and cost requirements throughout the entire product development process. Azapagic (1999) also discussed LCA application in process selection and design. On similar lines, Khan *et al.* (2004) proposed a life cycle indexing system—LinX—which facilitates LCA application in process and product evaluation and decision-making. Kobayashi (2005) presented a methodology and a software tool to establish an eco-design concept of a product and its life cycle by assigning appropriate life cycle options to the components of the product. He made a design support tool for efficiently planning product life cycles by using QFD and LCA data. Bovea and Wang (2003) introduced a novel approach for identifying environmental improvement options by taking into account customer preferences. The LCA methodology is applied to evaluate the environmental profile of a product while a fuzzy approach based on the 'House of Quality' in the QFD methodology provides a more quantitative method for evaluating the imprecision of the customer preferences.

In order to evaluate or select a solution idea or a design concept, other weighted rating methods are utilized (Pahl and Beitz 1988). In these methods, weighting of the evaluation criteria greatly affects the evaluation result. Total evaluations of eco-products have been reported (Williams *et al.* 1996, Zhang *et al.* 1998). In these evaluations, the weighting factors of the evaluation criteria were calculated using the analytic hierarchy process (AHP) (Satty 1980). Huang *et al.* (2004) combined three methods to evaluate the impact of packaging materials:

1. Life cycle assessment (LCA), a quantitative method, to assess environmental loading.
2. Analytic hierarchy process (AHP), a qualitative method, to obtain opinions from experts.
3. Cluster analysis to integrate the results of the former two methods.

The authors developed this method to provide integrated information and avoid a bias towards either a qualitative or a quantitative approach.

Product life cycle simulation (LCS) techniques have been proposed to evaluate the environmental burden and revenue of a company caused by single or multiple product life cycles from a medium-term or long-term viewpoint (Hoshino *et al.* 1995, Umeda *et al.* 2000, Murayama *et al.* 2001). LCS is useful for evaluating the business strategies or modular architecture for an eco-product. However, if the number of components or materials constituting the product is too large, calculations cannot be executed in a practically feasible time, because the number of possible combinations of life cycle options increases exponentially.

2.2 *Research approach*

This study proposes a new approach to DfE and a new way of integrating this design methodology with both the LCA technique and the economic aspects. The methodology develops an improvement cycle identifying environmental and economic break even point (BEP) between two design solutions. The combination of these two BEP curves defines four areas of economic and environmental advantage; therefore the designers will be able to make the most efficient choices from both the environmental and the economic point of view. This methodology can be used by the designers in the initial phases of development of a new product or in the re-design of an existing product.

The methodology proposed in general in figure 1 can be developed through a procedure composed of six steps:

1. *Definition of the order specifications and first trial layout*. The procedure begins with the analysis of product specifications requested by the client and the work environment conditions in which the product will be used. Therefore the designer can develop the first trial layout for the product. On the basis of the product specifications set it is possible to obtain as data output the basic parts lists (codes, assembly times, costs) for the product.
2. *Calculation of input and output flows and reduction of the modular complexity of the product*. A life cycle inventory (LCI) analyses is performed in order to evaluate input and output flows. Often the modular complexity of the product and the necessity to reduce design times as much as possible led to the need to select which items to include in the LCI. The traceability of all the suppliers and in particular of all the production processes of the components may prove to be an almost insurmountable limitation for the introduction of an integrated DfE system, both because of the material difficulty and the time needed to carry out the research and also because of some problems connected with the diffusion/spread of company know-how (it is necessary to have the executive designs and to know the production techniques adopted).
3. *Validation of the model*. *S*ubsequently it is necessary to validate the choice to exclude some sets of codes even at an environmental level so as to be able to demonstrate that the flows excluded are not of particular importance for the possible impact categories. This check must be carried out by doing an LCIA study for the single category of product.
4. *Definition of the alternatives and calculation of environmental BEP*. *A*fter determining the values of the flows involved, the time necessary for processing and assembling the components and the energy consumption of the firm, it is possible to calculate the environmental impact of the initial layout for the product. The improvement cycle continues with the attempt to find new design solutions and with the calculation of the environmental BEP between the old and new solutions. The calculation must be carried out for each impact category when there are variations in the manufacturing parameters.
5. *Calculation of economic BEP*. Subsequently a BEP analysis of the costs incurred by the client must also be developed. The two BEP analyses are referred to the same parameter.
6. *Choice of the best solution*. Finally, by comparing the two BEP values (environmental and economic) four possible alternatives are defined. The designer must choose the most efficient solution on the basis of the work conditions in which the product will be used.

3. Case study

Figure 2 shows the six steps of the procedure referred to above in section 2.2, and applied to an 'electrical distribution boards' set of products. The aim of this procedure is to improve the performance of the electrical distribution board, in terms of environmental and economic impact, not by intervening in the design of the single

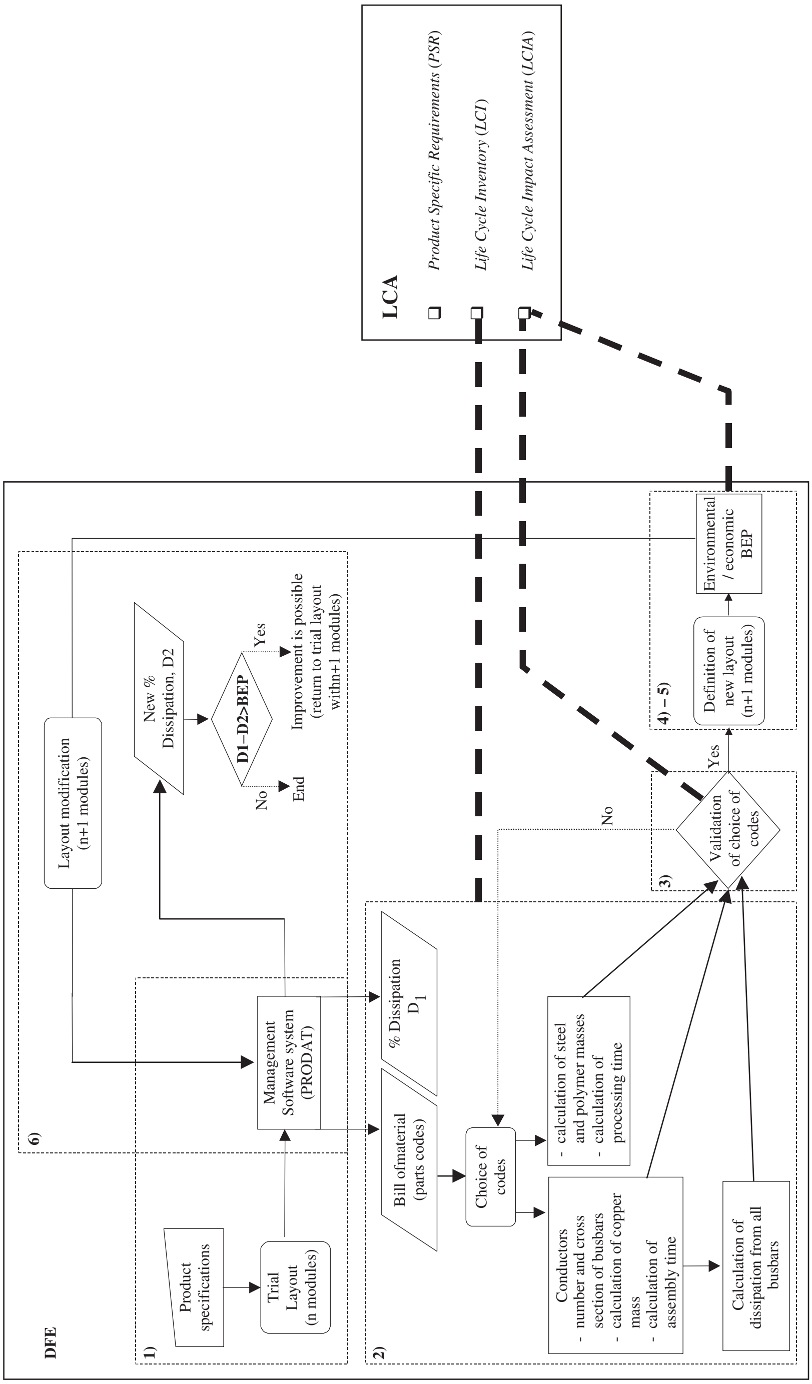

Figure 2. Steps of the procedure.

components (for example, circuit breakers), but rather by improving the assembly (changing the electrical distribution boards module number, *n*) and trying to limit energy consumption due to internal dissipation during use.

In order to integrate this procedure with the normal, design steps software has been used, and in some cases created, which is able to interact with the management software system of the firm used by the designers. In particular the newly created software programmes, interacting with each other, perform the procedure steps 2, 3, 4, and 5.

1. *Specifications of the product*. The first step in the procedure is to integrate the management software system used by the designers (PRODAT) with the specifications of the product requested by the client, the work environment conditions in which the electrical distribution board will be used and therefore the minimum number of modules necessary to contain the components which the board needs (trial layout). On the basis of the product specifications set it is possible to obtain as data output the basic parts lists (codes, assembly times, costs) for the product and the percentage of maximum energy dissipation of the board (D1) calculated considering the trial layout.
2. *The calculation of the mass flow*. The calculation of the mass flow for the assembly stage was carried out by means of the basic parts lists. The modular complexity of the product and the necessity to reduce design times as much as possible led to the need to select which items to include in the LCI. The list of components is made up of over 30 000 codes to be managed in a modular way according to the specifications of the board required by the client. For this reason an error in calculation of the masses equivalent to 5% of the total weight of the product was considered acceptable. Bearing in mind these considerations, some specific elements for manoeuvre, such as circuit breakers, isolating switches and all other elements that are involved in their set-up need not be analysed from the point of view of calculation of the flow of mass.
3. *Validation of choice of codes*. The high design complexity of the distribution board is compensated for at LCA level by the fact that the utilization stage is in fact the predominant one for environmental impact and therefore allows us to increase the error tolerance at the assembly stage. In the calculation of a single impact category referred to the whole life cycle an acceptable uncertainty equivalent to 5% has been set. This assumption originates from the awareness that there is a variance of between 5% and 10% in the LCI analysis data coming from different sources.
4. *Definition of the alternatives and calculation of environmental BEP*. It is possible to calculate the environmental impact of the initial layout (*n* modules) and the environmental impact of the new layout obtained by distributing the components over several modules ($n+1$ modules), and thereby reduce the dissipation during the distribution board utilization stage. The environmental impact due to the whole life cycle of the distribution board can be attributed to two different moments and causes:

   - Impact due to the component building and board assembly stage.
   - Impact due to the utilization stage of the board.

For some types of board the latter is responsible for more than 90% of the total impact per single category. This suggests that a possible solution for improvement could be brought about by a layout solution which increases the energy performance of the distribution board. At this point it is necessary to ensure that any improvements made at the level of environmental impact by these actions are not countered by an increase in the mass flows due to the increase in the raw materials used for the production of extra modules. The environmental BEP must therefore be calculated as a per cent dissipation of the maximum power of the module in a variety of working conditions.

5. *Calculation of economic BEP*. The two BEP analyses are referred to the same parameter: the percentage of dissipation of the devices which must be reduced in order to ensure that the new layout is economically convenient.
6. *Modification of layout*. The parameters of the new electrical distribution board layout are then integrated in the firm's management software system (PRODAT) which identifies the new dissipation (D2). Finally, by comparing the difference in dissipation between D1 and D2 and the two BEP values (environmental and economic) four possible alternatives are defined. The designer must choose the most efficient solution on the basis of the work conditions in which the electrical distribution board will be used.

3.1 *Approach and parameters used in the LCA study*

The LCA module interacts at different stages of the DfE procedure: the first stage involves the transmission of the data necessary for carrying out the LCI stage, the second concerns the model validation stage and the third the comparison between the environmental impact of the various layouts of the product.

3.1.1 Product specific requirements. The first step for using the LCA technique is to create the product specific requirements (PSR). The PSR defines the functional unit to be used, the system boundaries, and the results to be presented in the final report. PSR acts as a mutually agreed official document that all manufacturers of the same kind of product follow when developing their own environmental product declaration. In this way the results presented in EPDs for similar products, irrespective of producer, will permit easy comparison of relevant environmental parameters. Since no PSR existed for electrical distribution boards, the firm was obliged to develop guidelines for this device, in parallel with their own product-specific LCA analytical work.

In accordance with the guidelines for Goal and Scope Definition (ISO 14040) the parameters defined were:

1. *Object of analysis*. The object of analysis is the low tension distribution boards (<1000 V; 1250–6300 A) in accordance with the specifications in the CEI EN 60439 series regulations. The basic unit of an electrical distribution system, which we will identify as module, is made up of a box, a cover and a series of internal partitions. The modules can be installed as single units or in combinations of units, and take on particular layouts according to the

equipment housed and the clients' specifications (level of IP[1]). According to the specifications required, the box must allow the sub-division of the module into areas: the fixed parts area, the busbar area and the cables area.

2. *Function*. Distribution of electrical energy and control of mechanical devices in civil and industrial applications.
3. *Functional unit*. Due to differences in size, output and efficiency between single machines it is not meaningful, for comparative purposes, to specify resulting environmental impact per machine, but rather to relate this to a functional unit which is linked to operational requirements. The functional unit chosen for the group of products 'electrical distribution boards' is the capacity to distribute 1 MJ of electrical energy.
4. *Physical limits of the system considered*. The parameters which are ecologically important must be set, in order to be able to decide whether to exclude mass or energy flows, or any emissions which may be present in the system being considered. For all the life cycle phases of the product the input and output must be specified as follows:
   (a) Materials and energy going from the environment to the system;
   (b) Emissions and waste products going from the system to the environment.

Our analysis is for internal use only; therefore it is possible to use an approach which does not include all the phases of the product life cycle. We will analyse only those aspects which we consider important. The production site investigated is involved mainly in assembly operations. The finished components arrive in the firm from other factories, except for some elements which are finished on site because of their high level of design flexibility (for example the cutting of copper busbars). Bearing this in mind the life cycle investigation can be broken down as follows:

Distribution board component production stage. This is considered as carried out by the firm being analysed. The input and output flows are taken into consideration for the final environmental assessment. Production output represents the input for the distribution board assembly stage.

(a) Extraction and production of raw materials: from an initial quantitative analysis of the product 'electrical distribution boards' the number of components installed in the board proved to be, as previously mentioned, a problem to be addressed. For this purpose, for the materials used in the distribution board and assembled only in the firm, we adopted the simplification of assessing their contribution to the analysis only in terms of their weight, of the material used and the technology required for producing them, without going into too much detail about the single elements. For example, for the materials in sheet metal we considered their weight and the fact that they were produced using cold rolling. This is one type of 'cradle to gate' assumption. The transport from the various suppliers to the factory has also not been considered.
(b) Production stage emissions and waste; see point (a).

Distribution board assembly stage. This is an integral part of the system.

[1] The level of IP is a determinant of design because it defines the capacity of the board both to impede the access of foreign bodies such as dust or water, and to prevent any contact between the workers and the electrically charged parts.

(a) The process of assembly of the components produced by the various suppliers. The predominant flows in this phase of the life cycle concern mass (input) coming from the previous stage and the energy consumption within the firm which are a satisfactory approximation of any finishing carried out (cutting, . . .)
(b) Emission and waste referred to the relative flows.

Distribution board utilisation stage. This is an integral part of the system.

(a) The most important parameter for this stage of the life cycle is the energy which is dissipated during use. The expected life of the distribution board must be set so as to assess the environmental performance. The expected life has been set at 15 years. Transport to the final installation destination has been ignored.

The disposal phase of the electrical distribution board has been ignored since the materials included in the analysis can all be recycled.

5. *Time limits of the system considered*. Limits to the system connected with the data collection reference time. All the data refer to production in 2004 in the factory studied.
6. *Environmental limits of the system considered*. Limits to the system connected with the data collection reference place. All the data concerning component production refer to European suppliers, as do the data which refer to utilisation of the board. On the contrary the data which refer to energy consumption during the assembly stage are national.
7. *Data quality*.

In this case direct data are:

(a) All the data which refer to the calculation of mass flows during the production and assembly stages.
(b) All the data which refer to the calculation of energy flows during the assembly stage.
(c) All the data which refer to the calculation of energy flows during the utilization stage.

Indirect data are:

(d) All the data which refer to the component production stage.

8. *Units of measurement*. SI units of measurement are used.
9. *Allocations*. This sets the way in which the flows of mass and energy have been obtained. The calculations of mass flows have been obtained from the parts lists. The data for energy flows for the various production stages were obtained directly on site by referring to consumption for the year 2004. The data concerning energy consumption during the utilisation stage are partly obtained from the engineering guidelines used during design and partly calculated using studies of distribution board operations.
10. *Level of analysis*. The analysis is a simplified LCA.
11. *Acceptable error*. The maximum acceptable error for each single category of impact referred to the whole life cycle is 5%; this is in fact the variance which exists between the data for environmental impact when several data bases are compared.

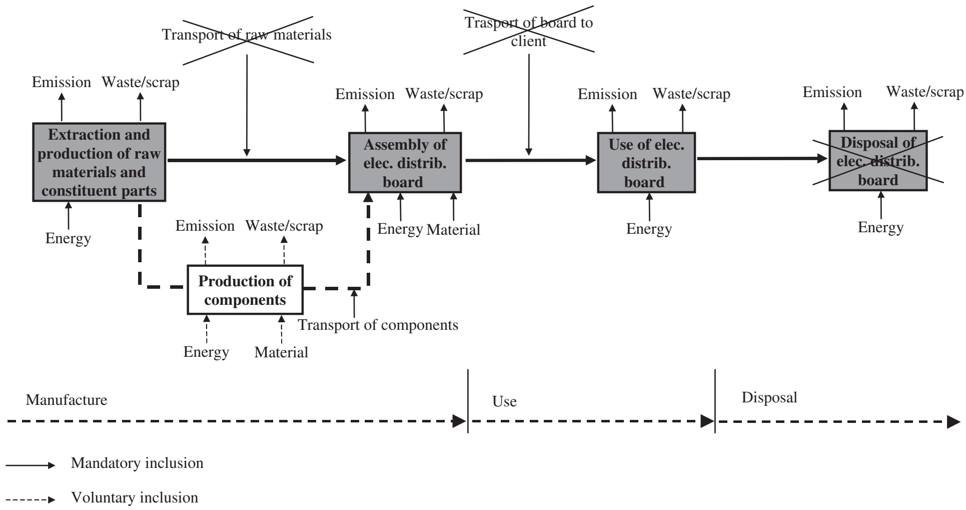

Figure 3. Electrical distribution board life cycle flow chart.

3.1.2 LCI: life cycle inventory. The second stage of the LCA investigation is life cycle inventory. In accordance with ISO 14041 this stage involves the collection of data concerning the processes and the various calculation procedures. The relationships between the system produced and the environment are defined; ISO 14041: 'A system produced is a set of processes connected by flows or intermediate products which allow a specific function to be obtained' (ISO 1998). Information is collected from the product development office regarding material amounts, and machine performance such as power and efficiency. Data is added concerning emissions to air and water, generation of waste and energy consumption (figure 3).

3.1.3 LCIA: life cycle impact assessment. An LCA calculation software called Eco Lab[2] has been used to process results. Central to the software is an extensive material database containing internationally agreed environmental characteristics. This software produces final reports showing quantified impact related to the global environmental threats (see appendix 1):

- Global warming potential (GWP).
- Acidification (AP).
- Depletion of the ozone layer (ODP).
- Photochemical oxidant formation (POCP).
- Eutrophication.

3.2 *Application example*

In order to better explain the procedure proposed earlier in section 3 this case study illustrates its application to the design of a set of electrical distribution boards which

[2] The computerized LCA-system Eco Lab issued by Nordic Port AB, Varbergsgatan 2C, S-412 65 Gothenburg, Sweden.

Table 1. Assembly stage flows.

Steel mass (kg)	1.40E+02
Copper mass (kg)	5.10E+00
Polymer mass (kg)	1.12E+00
Electrical energy (MJ/sec)	2.18E−01
Fuel oil (kg/sec)	1.39E−02
Diesel fuel (kg/sec)	3.62E−03
Assembly time (sec)	8.35E+03

will henceforth be referred to as 'A'. The simplest structure for this electrical distribution board consists of the use of one single module to allocate all the components. Analysis of the parts lists showed the mass flows which are involved in the assembly stage. Three different flows have been identified among the codes which are important for the analysis:

- Code by piece identifying components made up of cold rolled steel.
- Code by piece identifying components made up of electrolytic copper.
- Code by piece identifying components made up of polymers, in particular high impact polystyrene.

For the set of 'A' products the mass and energy flows depend on the client's specific requirements and on the work environment in which the electrical distribution board will be used. For example, table 1 shows the principal flows present during the various phases in the life cycle of a set 'A' electrical distribution board, for which the requirements were a low protection index (IP), temperature of 35°C and a current of 3500 A.

It is assumed that during working life the only flow is caused by the dissipation of electrical energy by means of heat, and that this makes the greatest contribution from the point of view of environmental impact. The heat developed is dissipated owing to the difference in temperature between the distribution board and the external environment, thereby leading to heat exchange by radiation, convection and conduction.

Numerous factors influence this phenomenon, in particular:

- The size of the single modules of the board which help the exchange if their size increases.
- The level of IP: if this increases it obstacles flows towards the external environment.
- The low temperature of the environment in which the board is installed.
- The internal partitions.
- The arrangement of the sources of heat.

The environmental factors, such as temperature and level of IP depend on the needs of the client, but the size and the arrangement of the sources of dissipation inside the distribution board are the result of the layout chosen for the board itself, and must therefore be attributed to the designer.

As has already been explained, in order to accelerate the LCI phase some groups of codes which were not considered to be important were excluded from the analysis, for example the functional elements for manoeuvre, such as switches, isolating

Table 2. Utilization stage flows.

Dissipated energy main busbars (MJ)	6.48E+03
Dissipated energy module (MJ)	1.85E+05

Table 3. Materials excluded from the analysis.

Materials	Mass excluded	Errors%
Steel (kg)	2.79	1.99
Copper (kg)	0.00	0.00
Polymer (kg)	0.20	17.85
Total (kg)	2.99	2.04

Table 4. Harmful substances for AP.

Output air + water	Quantity (g)
Ammonia NH_3	8.145
Nitrogen oxides Nox	4540
Sulphur dioxides SO_2	6180

switches, etc. For the example already considered in tables 1 and 2 the results are shown in table 3.

The value of the total mass excluded remains under 5% (limit which was set in the definition of the PSR).

To quantify the various impacts of the flows the following method was applied:

1. *Identification of any harmful substances emitted per impact category (classification)*. For example, for the acidification impact (AP), expressed in kg of SO_2 equivalents, out of all the emissions caused by the cold rolling production process only those which concern this impact category are shown in table 4 (the amounts emitted refer to one tonne of product).

The sources of the data used are mainly bibliographical and public and include the principal European LCI databases such as ETH-ESU (1996), BUWAL (1994, 1996) and APME (199) (see references).

2. *Identification of the CF (characterisation factor) for each single substance identified above (characterization)*. According to ISO-TR 14025 (ISO 2000) the harmful substances for this impact category are shown in table 5:
3. *Calculation of the PI (potential impact) of the single raw material or the energy for each single impact (characterization)*. In the above-mentioned example the potential impact of the material 'steel' on the AP category is 9.70E−03.[3] Table 6 shows the potential impact (PI) of the flows for all the life cycle phases.

[3] The values shown in tables 4 and 5 give the following results: (1.60E+00 · 8.145 + 5.00E−01 · 4540 + 1.20E+00 · 6180)/1000000 = 9.70E−03 (kg of SO_2 eq./kg_{steel}).

Table 5. Characterization factor for AP.

List of substances for AP	CF
Ammonia	1.60E+00
Nitrogen oxides (as NO_2)	5.00E−01
Sulphur dioxide	1.20E+00

Table 6. Potential impact for each impact category.

	AP	NP	POCP	ODP	GWP
Steel	9.70E−03 (See this value in note 3.)	7.48E−04	8.64E−04	2.48E−07	3.18E+00
Copper	1.44E−01	0.00E+00	5.76E−03	0.00E+00	3.00E−01
Polymer	1.93E−02	1.57E−03	1.04E−03	2.97E−06	2.90E+00
Electical energy	3.60E−02	1.82E−03	8.84E−05	0.00E+00	1.60E−01
Diesel fuel	2.33E−01	3.67E−02	1.49E−03	0.00E+00	3.04E+00
Fuel oil	6.37E−01	6.25E−02	2.12E−03	0.00E+00	3.50E+00

Table 7. Total impact for each category.

Category	Total impact of the materials during the manufacturing stage
AP (kg of SO_2 eq.)	2.12E+00 (See this value in note 4.)
GWP100 (kg of CO_2 eq.)	4.51E+02
NP (kg of PO4 3– eq.)	1.07E−01
ODP (kg of CFC11 eq.)	3.87E−05
POCP (kg of C2H4 eq.)	1.52E−01

4. For each category the *total impacts*, referred to the production and the component assembly stages, have been calculated (the result of the quantity of material or energy by the relative PI). The results are shown in table 7.[4]

3.2.1 Reduction of the modular complexity and validation of the model. The values in table 7 are the basis for checking the choice and for calculating the error made by excluding some codes. The exclusion of one code must also involve the assessment of its effects on a single impact category. In fact it is possible that, even if of little importance in terms of mass, the raw materials excluded may determine some important contributions for environmental impact. It is therefore necessary to calculate the CF_{limit} for each impact category. The necessary steps, on the basis of indications given by 14040 standards, are the following:

1. The overall contribution for each category of impact made during the distribution board production stage is defined. If a maximum percentage

[4] The values shown in tables 1 and 6 give the following results: $9.70E{-}03 \cdot 140.05\,kg + 1.44E{-}01 \cdot 5.10\,kg + 1.93E{-}02 \cdot 1.12\,kg = 2.12$ (kg of SO_2 eq.).

Table 8. Emission factor for AP.

	Emission factor (AP)
Steel	2.94E−03 (See this value in note 7.)
Copper	1.20E−01
ABS	5.80E−03

uncertainty (AU%) of 10% is accepted, then the negligible potential impact for that impact category will be:

$$AU = \frac{\text{Impact}_{TOT} \cdot AU\%}{100} \text{(for example AP see note }^{5}\text{)}$$

2. Calculation of the total mass excluded from the analysis = CE (cumulative excluded). For the module 'A' being studied this is equal to 2.99 kg.
3. Calculation of the EF (emission factor): the emission factor is the sum of the quantities of all the important emissions for the impact category, given by kg of substance excluded. Since in this case three substances were excluded (steel, copper and ABS) the calculation of the EF was carried out as a weighted average of the EF of the three raw materials. From the above mentioned databases it is possible to extract all the substances emitted during the production cycles of the three raw materials. For each raw material and for each category the harmful substances ('S') were identified and the quantities were multiplied by the relative CF. This number was divided by the number of the harmful substances ('n') and by the CF average $= \Sigma_i^n CF_i/n$ (see note [6]), for those substances. In this way the EF for raw material and impact category was obtained:

$$EF_{(\text{rawmaterial; impact category})} = \frac{\sum_i^n (S_i \cdot CF_i)}{(n \cdot CF_{\text{average}})}$$

Table 8 shows the emission factor values for the AP impact category (see note[7]).

Three $EF_{(\text{raw material})}$ exist for each impact category. To determine the EF of the impact category these three values were averaged according to their importance in the module examined (see note[8]):

$$EF_{(\text{impact category})} = \frac{\left(\sum (EF_{(\text{raw material; impact category})}) \cdot (\text{Mass}_{(\text{raw material})})\right)}{\text{Mass}_{\text{tot}}}$$

[5] $AU(AP) = 2.12 \times 0.1 = 2.12E{-}01$.

[6] For example for the raw material steel and the AP impact category in table 5 the result obtained is: $CF_{\text{average}} = (1.60E{+}00 + 5.00E{-}01 + 1.20E{+}00)/3 = 1.10E{+}00$.

[7] $EF_{(\text{steel; AP})} = (1.60E{+}00 \cdot 8.145 + 5.00E{-}01 \cdot 4540 + 1.20E00 \cdot 6180)/(3 \cdot 1000000 \cdot 1.10E{+}00) = 2.94E{-}03$.

[8] Tables 1 and 8 give the following results: $EF_{AP} = (2.94E{-}03 \cdot 1.40E{+}02 + 1.20E{-}01 \cdot 5.10E{+}00 + 5.80E{-}03 \cdot 1.35E{+}00)/146.5 = 7.04E{-}03$.

Table 9. Characterization factor limit for each impact category.

Category	CF_{limit}
AP	1.00E+01 (See this value in note 9.)
GWP100	1.37E+04
NP	1.75E+01
ODP	4.00E+01
POCP	5.07E−03

Table 10. Neglected impact for the GWP 100 category.

Total neglected impact	8.86
Per cent error on production + assembly	1.960%
Per cent error on life cycle	0.015%

4. Calculation of the CF_{limit} for each impact category (see note[9]):

$$CF_{limit} = AU/(CE \cdot EF_{(impact\ category)})$$

Table 9 shows the values of the CF limit for all the impact categories.

In order to determine the errors caused by the exclusion of some codes it is necessary to verify for each impact category which substances emitted during the production cycles of the raw materials have a $CF > CF_{limit}$. The values found in the databases for the '*A*' product give the following results: NP, AP, and ODP do not have a CF greater than the limit. Therefore for these impact categories the error generated by the model is not meaningful. For the categories GWP 100 and POCP some substances have a greater CF and in these cases the error has been calculated:

$$\text{Neglected impact}_{\text{raw material}} = \sum_i^n Pi \cdot Kgi_{(rawmaterial\ excluded)}$$

where P_i is the potential impact (PI) of the raw material excluded and Kg_i is the mass.

By adding the neglected impacts of the three raw materials it is possible to calculate the Neglected $\text{impact}_{\text{Total}}$ and therefore the total% error.

$$\text{Total \% error} = (\text{Total impact}/\text{Neglected impact}_{\text{Total}}) \cdot 100$$

For the GWP 100 category the substances emitted by steel which are higher than the CF_{limit} are 'Halon 1301' and 'Halogenated HC' while several types of CFC emitted by ABS exceed the CF_{limit}. The results shown in table 10 have been obtained by calculating the per cent error.

For the POCP category the substances emitted by steel and polymer which exceed the CF_{limit} are some 'Aromatic HC'. The results shown in table 11 have been obtained by calculating the per cent error.

In terms of environmental impact the error made by excluding the codes is much lower than the maximum (set at 5% in the PSR) for each impact category on the lifecycle. For this reason the model can be considered valid for the subsequent

[9] For example the AP category gives: $CF_{limit} = 2.12E{-}01/(2.99 \cdot 7.04E{-}03) = 1.00E{+}01$.

Table 11. Neglected impact for the POCP category.

Total neglected impact	0.012
Per cent error on production + assembly	8.02%
Per cent error on life cycle	0.03%

analysis aimed at improving the environmental performance of the distribution board itself. This validation analysis carried out for the 'A' set of electrical distribution boards was repeated with other types of distribution boards. The study was repeated for simpler and more complex distribution boards so as to cover all the possible arrangements, and in all cases the exclusion from the analysis of some groups of codes did not lead to meaningful errors. It can therefore be deduced that this approach can be considered valid for the design of all types of electrical distribution boards. The groups of codes which can be neglected in the assessment of the total impact have been defined so as to accelerate the DfE procedure.

3.2.2 Environmental break even point. The electrical distribution board 'A' has some fixed installation equipment without distribution bars and, in its simplest form, does not have any internal partitions (trial layout). The dissipations are calculated as the sum of those deriving from the equipment (module[10]) and those from the copper conductors (main circuit breakers and distribution and off-set bars). Having defined the set of conductors, the electrical characteristics of the bars are set, and the dissipation becomes a function only of the supply current, which is a design feature. The density of the equipment and its layout within the module determine the per cent of the dissipative capacity of the module used, compared with the total. The environmental improvement attempt for product 'A' consists in substituting single module set ups with solutions which have more than one module and verifying to what extent this dissipation per cent has been reduced when the equipment is arranged in a different way.

A possible solution to this problem is to find the break even point (BEP) by defining to what extent the per cent dissipation of the module must be reduced in order to justify a solution which uses more than one module. The calculation must be carried out for each impact category when there are variations in the manufacturing parameters (level of protection IP) and in the supply currents. It is necessary to demonstrate that at the environmental level any improvements made by these actions (energy dissipated from the module) are not countered by an increase in the mass flows due to the greater amount of raw material used in order to manufacture more modules.

Any variation in layout which involves the arrangement of the equipment required by the client in two modules brings about the following increase in the mass and energy flows:

- The mass and energy flows during the manufacturing and assembly stages double: in fact even the copper busbars undergo this process because only the

[10] Electric power dissipated from the module is $P_{\text{module}} = I^2 R_{\text{base module}} + P_{\text{cont}} + P_{\text{constant}}$. Where I is the current passing through the equipments; $R_{\text{base module}}$ is the equipment resistance; P_{cont} is the electric power of the main contacts; P_{constant} is constant power dissipated from the other components being charged.

Table 12. Environmental BEP.

Current [A]	BEP% (AP)	BEP% (NP)	BEP% (POCP)	BEP% (GWP100)
150	0.73	1.18	2.56	1.61
350	0.74	1.18	2.57	1.61
550	0.75	1.20	2.59	1.63
...				
3500	2.24	3.50	7.19 (See this value in note 11 and 12.)	4.19
...				
5400	2.88	3.79	9.29	4.73
5600	3.04	3.92	9.51	4.88
5800	3.20	4.15	9.87	5.04

main ones are present and these must cover the whole width of the new layout. The cross-section of the busbars and the number of conductors per stage do not vary because the supply current remains the same.

- The dissipations from the main busbars during use double for the above mentioned reason.

To calculate the environmental BEP it is necessary to calculate for each impact category (see note[11]):

$$IMP_{mod2} = IMP_{tot1} - 2 \cdot IMP_{ass} - 2 \cdot IMP_{main\ busbars}$$

where IMP_{tot1} is the impact of the whole life cycle in the standard layout (with one module in the case of product 'A'); IMP_{ass} is the impact of the whole life cycle before use in the standard layout (with one module in the case of product 'A'); $IMP_{main\ busbars}$ is the impact of the dissipation of the main busbars in the standard layout (with one module in the case of product 'A'); IMP_{mod2} is the value of the environmental impact of the equipment (module) which the re-designed distribution board must have at break even point.

The environmental BEP, expressed as a percentage of reduction in dissipation, is therefore calculated for each single impact category as: $1 - (IMP_{mod2}/IMP_{mod1})$, where IMP_{mod1} is the value of the environmental impact due to the equipment (module) in the standard layout (see note[12]). Analysis carried out with varying supply currents for the product in set 'A', studied in the previous chapter, provided the results shown in table 12.

The analysis of the ODP impact category was not carried out for any type of distribution board since the potential impact of electrical energy for this category is zero.

[11]For example, for the type 'A' distribution board with low protection index (IP), temperature of 35°C, a current of 3500 A and one module, from tables 1, 2 and 6 it is possible to calculate for the POCP impact category: IMP_{ass} (POCP) = (1.40E+02 · 8.64E−04) + (5.10E+00 · 5.76E−03) + (1.12E+00 · 1.04E−03) + (2.18E−01 · 8.35E + 03 · 8.84E−05) + (1.39E−02 · 8.35E + 03 · 1.49E−03) + (3.62E−03 · 8.35E + 03 · 2.12E−03) = 6.04E−01 [kg of ethylene equivalent]. $IMP_{main\ busbars}$ (POCP) = 6.48E + 03 · 8.84E−05 = 5.73E−01 [kg of ethylene equivalent]; IMP_{mod1} (POCP) = 1.85E + 05 · 8.84E−05 = 1.64E + 01 [kg of ethylene equivalent]; IMP_{tot1} (POCP) = IMP_{ass} + $IMP_{main\ busbars}$ + IMP_{mod1} = 1.75E+01 [kg of ethylene equivalent]; P_{mod2} (POCP) = IMP_{tot1} − 2 IMP_{ass} − 2 $IMP_{main\ busbars}$ = 1.52E+01 [kg of ethylene equivalent].

[12] In the case shown in note 11, BEP (POCP) = 1 – (1.52E+01/1.64E+01) = 0.0719.

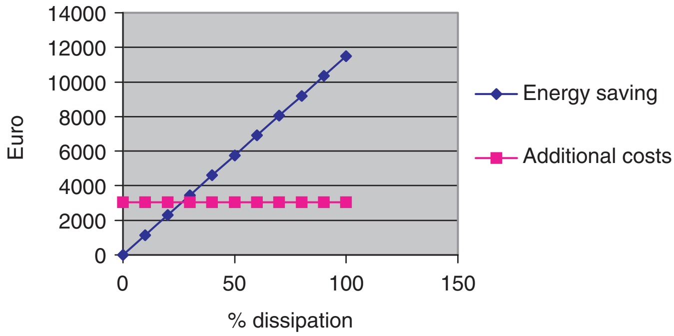

Figure 4. BEPcosts, Module 'A', IP 30/40.

The most significant category from the environmental point of view is POCP owing to the high CFC and halogen emissions in the mass flows. For this reason, when trying to obtain an improvement in all the categories by changing the layout, this category of impact was taken as a reference and the overall BEP line (figure 5) was calculated as: 4 × BEP%(POCP) (see note[13]).

3.2.3 Economic/environmental break even point. Any attempt to make manufacturing industries aware of the overall effects of their production processes must necessarily include an analysis of the expenses that the industries incur in order to reach their targets. It must be taken into consideration that modifications in layout, in order to obtain improvements in the various impact categories, generate an increase in the components of the electrical distribution board and an increase in the assembly time. On the other hand the percentage energy saving, considering a 15-year lifecycle of the distribution board, reduces the economic burden on the client.

The parameters which have been taken into consideration are: costs of the components; costs of labour; costs of energy due to dissipations. Other possible sources of costs, such as the need for the purchaser to have a larger space available in order to be able to set up a distribution board with more than one module, have been ignored.

Figure 4 shows the savings and the additional costs involved in changing the layout of the electrical distribution board of the 'A' group used as an example throughout this chapter, according to the varying per cent of reduction in dissipation.

The BEP for costs is obtained with a dissipation of 26.47%.

The overall results, shown in figure 5, indicate the presence of four areas of economic advantage resulting from the modification of the layout of the electrical distribution board. On the basis of the client's requirements and according to the conditions in which the distribution board will be used, the designer can easily choose the best solution.

The graph in figure 5 illustrates that with currents >3000 A, if it is possible to reach the environmental BEP there is also an overall cost benefit for the client.

[13]In the case shown in note 11, BEP line = 4 · 7.19% = 28.78%.

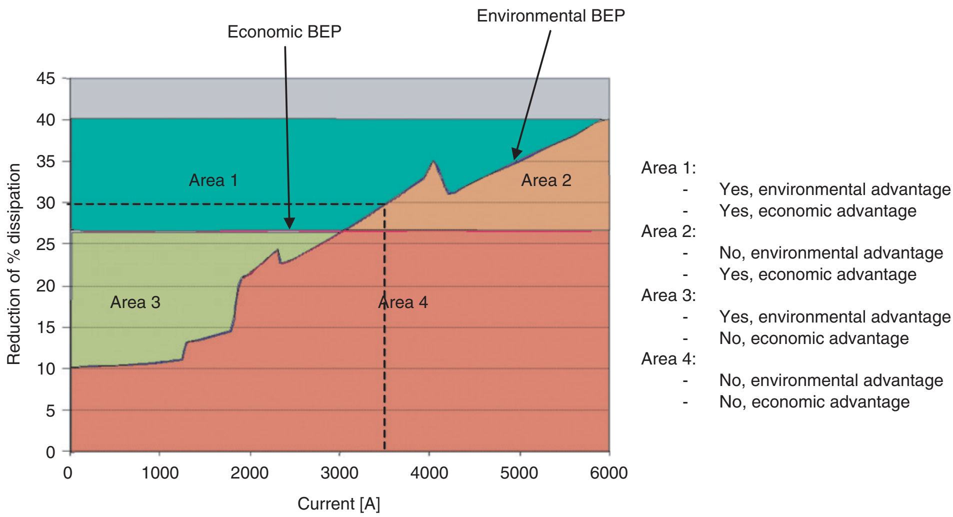

Figure 5. Environmental BEP + Economic BEP analysis.

The extent of the economic benefit can be seen in figure 4. By repeating the analysis for other groups of electrical distribution boards we found that there is a better compromise between environmental improvement and economic competitiveness for modules which have a simple design and greater dissipation, while for the other modules it is not so easy to identify an arrangement which is sustainable from both points of view. The analysis provides different results according to the type of distribution board: the sets of simpler electrical distribution boards have relatively low environmental BEP values (for POCP the maximum reduction is 40%). In fact the total dissipation is almost entirely due to the module and the mass flows are low. The economic analysis highlights the same trend.

For other groups of electrical distribution boards with more complex layouts many conductors are present and the equipment is much less able to dissipate and therefore the per cent reductions in order to reach the BEP are very high, even with low supply currents. The cost analysis for these modules provides BEP values which can seldom be reached, varying from 80% to 90%.

4. Discussion and final conclusions

The aim of this paper was to combine environmental and economic considerations with sustainable development. The study proposed a new way of addressing the issue of Sustainable Product Lifecycle by integrating DfE methodology and the LCA technique. The work developed in the firm that produces 'electrical distribution boards' can be divided into two phases:

- In the first phase a database was built in which the impact value for the categories AP, GWP, ODP, NP and POCP was reported, for each important item, of the 'electrical distribution boards' components. This first part of the work was simplified by selection of the most important items and subsequent validation (section 3.2.1). This activity allowed the designers to eliminate from LCA analysis hundreds of component, without compromising the soundness of the study.

- In the second part of the work software was developed using VB. This application interfacing with the database and with the management software of the company (PRODAT) could help the designers to perform the best choice when it is necessary to modify an existing product or when customers require new technical specifications. Whenever designers have a new project, they will have to fill in a software form, defining the level of IP, the current to supply (A), the number of poles, the temperature of the environment in which the board will be installed, etc. Using this information this software can evaluate the components necessary for the project, assessing the component raw materials and defining the minimum number of modules needed to contain all the equipment. Moreover, for this configuration the software calculates for every impact category: the impact of the production and assembly phases, the impact given by main busbars dissipation, the impact produced by module dissipation and therefore the total impact. At this stage it is possible to obtain the environmental BEP in the hypothesis of adding a new module (section 3.2.2). This is an iterative process, progressively increasing the number of 'electrical distribution boards' modules. The advantage of adding a new module, from the environmental point of view, will be evaluated by the difference between the per cent of module dissipation in the initial configuration (D1) and in the final configuration with an additional module (D2). The reduction of per cent dissipation (D1−D2) should be greater than environmental BEP. Moreover this software allows the designers to calculate the additional costs due to a new module, the profits given by energy saving and consequently the economic BEP. The choice to insert a new module will be developed if the point identified by (D1−D2) and by the current is in Area 1 (figure 5).

Following these steps the procedure proposed is general and can also be applied to other types of products by expanding the database to include new component items and assessing their impact. Moreover, the method for calculating an economic/environmental BEP could be used by designers in other industries by adapting the ideas proposed in this paper.

This study highlighted some important problems which must be resolved by any industry attempting to create a methodology that integrates LCA techniques and DfE approach:

- The modular complexity of the product and the need to reduce design times imposed a choice of items to be inserted in the LCI. This is a very serious problem which nearly all manufacturing firms have to resolve. In fact, products with a great degree of modularity can frequently be found in manufacturing industries. The client can personalize these products to a great extent by choosing from a range of intermediate materials which are able to characterize the product purchased.
- The choices made in the previous step, when validated using LCA methodology, are used to create groups of codes which can be excluded from the study *a priori*, thereby further simplifying the tasks of the designer.

- The calculation of economic/environmental BEP is only possible if some significant parameters are identified (in this study, the per cent of dissipation and the current supplied). These parameters must represent a whole range of products (in this case electrical distribution boards) and for any variations in the parameters there must be a correlated variation in the costs and the environmental impact.
- In this type of study some of the simplifying hypotheses made in chapter 3.2, for example the exclusion of some components or the exclusion of some stages in the life cycle of the product, are acceptable for various reasons:
  - since a comparative LCA analysis was performed between two possible solutions (therefore activities which are common to the two solutions are excluded);
  - there is a variance of between 5% and 10% in the LCI analysis data coming from different sources. Therefore, the panel set up to carry out this study decided to fix an acceptable uncertainty equivalent to 5% in the calculation of a single impact category referred to the whole life cycle.

The basic idea behind this DfE methodology is to bring environmental expertise directly to the designers, either by integrating the environmental expertise into the design process or by using a software tool that 'speaks the language of the designers' and is integrated in their workflow. Thanks to the integration of the DfE tools in their daily workflow, the designers are able to assess the environmental performance of different design alternatives without being LCA experts and without additional effort. DfE tools calculate the environmental consequences of the design alternatives by using datasets and methodologies, which are integrated into the DfE database. The DfE tools provide algorithms and methodologies to calculate the environmental consequences of the current design alternative on the total life cycle of the product.

This work is part of a programme of activities which concern all the most important products of ABB Italia SpA aimed at obtaining Environmental Product Declarations (EPD).The EPD development process has created a great interest in environmental issues. It is important to point out that for a customer to be able to compare products from different suppliers, the product presentations must be standardized. The use of PSR provides a standardized method for creating an EPD to indicate environmental performance. It is also a long term aim to use the EPDs to make the customers more aware of the environmental aspects connected with the products. These aspects are just as important as price, quality, delivery conditions, etc.

The environmental performance obtained thanks to the application of DfE (Design for Environment) methodology during the project design development stage are worthy of note.

The procedure set up may have future developments with the introduction of other DfE concepts:

- use of recyclable thermoplastic resins to partly replace the thermosetting resins;
- marking of the plastic components to help their identification and end of life recycling/recovery;

- use of design solutions to simplify the dismantling of the distribution board at the end of its life, which, by allowing separation of the individual components, encourages its recycling and/or its correct waste disposal management.

Appendix 1

Acidification, AP. Acidification originates from the emissions of sulphur dioxide and oxides of nitrogen. Characterization model: model adopted by the CML (Centre of Environmental Science) in Leiden-NL (Heijungs *et al.* 1992, updated 1998). Characterisation factor: KG of AP (acidification potential). Indicator: kg of SO_2 equivalent.

Eutrophication. Nutrients (mainly nitrogen and phosphorus) from sewage outfalls and fertilized farmland accelerate the growth of algae and other vegetation in water. Characterisation model: model adopted by the CML (Centre of Environmental Science) in Leiden-NL (Heijungs *et al.* 1992, updated 1998). Characterization factor: kg of NP (nutrification potential). Indicator: kg of PO_4^{3-} equivalent.

Global warming potential, GWP. Some of the gases in the Earth's atmosphere (in particular water vapour and carbon dioxide) have an ability to absorb infra-red radiation. Characterization model: model adopted by the IPCC (Intergovernmental Panel on Climate Change) (Houghton *et al.* 1994, 96) Characterization factor: kg of GWP 100 (global warming potential over a time horizon of 100 years). Indicator: kg of CO_2 equivalent.

Ozone depletion potential, ODP. Ozone forms a layer in the stratosphere protecting plants and animals from much of the sun's harmful UV radiation. Characterization model: model adopted by the WMO (World Meteorological Organization) (updated 1999). Characterization factor: kg of ODP (ozone depletion potential in stationary conditions). Indicator: kg of CFC-11 equivalent.

Photochemical ozone creation, POCP. Photochemical ozone or ground level ozone is formed by the reaction of volatile organic compounds and nitrogen oxides in the presence of heat and sunlight. Characterization model: model adopted by UNECE (United Nations Economic Commission for Europe 1999). Characterization factor: kg of POCP (photochemical ozone creation potential). Indicator: kg of ethylene equivalent.

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