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# THE INFLUENCE OF MULTIPLE LIFE CYCLES ON THE ENVIRONMENTAL IMPACT OF A PRODUCT

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## ABSTRACT

One of the design problems of business-to-consumer products results from their increasingly short lifetimes. The technological changes, associated with the evolutions of use, lead the companies to renew their product lining more and more early. Components that could be used in new products are often wasted. Remanufacturing offers a promising solution to the issue of waste. But remanufacturing is economically and environmentally beneficial only if the product and its life cycle are designed to account for its reuse.

This article proposes green design of reusable modules with environmental and economic evaluations for multiples lifecycles (MLCs). We introduce parameters such as number and duration of cycles and the number of reusable modules. We tested this approach by comparing three espresso machines. The test showed that product decomposition in modules with multiple life cycles for reusable modules is environmentally and economically attractive.

*Keywords: LCA, Modularization, Remanufacturing, Multiples Life Cycles (MLC).*

## 1 INTRODUCTION

The introduction of environmental dimension in design became a priority last decade. The prospect of seeing mining and energy resources becoming exhausted in the medium term, together with associated environmental problems [1] should persuade the great industrial nations to reconsider how they manufacture and consume in order to create a new model for sustainable development.

The Brundtland report defines sustainability as: “the ability of current generations to meet their needs without compromising the ability of future generations to meet their own needs” [2]. This doctrine is built on three pillars: environmental protection, economic growth and social equity.

Today there is a pressing need for new strategies for sustainable development, whether it involves precious material recycling or the reuse of components at high added-value. Under pressure from the market and from customers who always want better technology, industry generates more high-tech products with an accelerated obsolescence today than ever before. These products, although discarded after a certain period of use, often remain functional. Most of their components could be reused in the manufacture of new products.

In addition to producing economic benefits, remanufacturing makes it possible to comply with the Waste Electrical and Electronic Equipment (WEEE) Directive, which imposes minimum rates of recycling, reuse and energy valorization [3] on the manufacturer. However, the methods suggested at the present time present major obstacles to multiple remanufacturing. The aim of this article is to address this technology gap by proposing a method which make it possible to meet the new requirements for sustainable development by decreasing consumption of resources and production of waste and supporting a new model of production. The new model helps to assure quality of life in the new economy.

The first section of this paper reviews the literature in the fields of remanufacturing and modular products design (Design for Modularity), including the lack of viable remanufacturing methods. In the second part, we propose a methodology to evaluate existing products, starting from modular groupings operating according to definite criteria (values, reliability, technology, materials, etc). The evaluation is based on an analysis of product life cycle alternatives (the number of reusable modules, product lifetime and the number of use cycles under consideration for each module). In the third part of the paper, we test our approach by comparing three espresso machines (a traditional machine without doses, a machine with aluminum doses and a machine with plastic doses). We summarize the benefits and limits of this approach in the last section.

## 2 LITERATURE REVIEW

The literature review shows that interest in remanufacturing is growing [4] [5]. Remanufacturing is defined as "the process of returning a used product to at least Original Equipment Manufacturer performance specification and giving the resultant product a warranty that is at least equal to that of newly manufactured equivalent" [6]. The definition draws from several design fields: evaluation of the remanufacturability and redesign of products to facilitate remanufacturing [7] [8] [9], research on remanufacturing operations (disassembly, cleaning, inspection and sorting, reconditioning, reassembly) [4] [5], environmental analyses [10] and economic analyses [11] [12]. Much of the literature treats only one aspect of the field.

Much research [13] [14] [15] has investigated how to optimize the disassembly of products for their recovery. The complexity increases with the number of components and the time required to dismantle varies depending on several parameters (interconnection of the components, joint types, direction of dismantling, etc). In 1997, Gungor proposed an algorithmic method to obtain an optimal sequence of disassembling [13] but this method does not account for the economic and environmental aspects. Completely dismantling a product in the shortest possible time would be too expensive to justify. In fact, remanufacturing must consider many criteria, as Kara notes [16]: "Full disassembly of a product tends to be unproductive due to technical and cost constraints". Zuidwijk says "a product recovery strategy determines the degree of disassembly of a product and the assignment of recovery options" [17].

According to [17] Zuidwijk, four options of valorization can coexist:

- Remanufacturing on a component level, which implies complete dismantling
- Recycling materials after complete dismantling
- Recycling materials after partial dismantling to respect quotas
- Setting in discharge.

One option is not mentioned: that which privileges an optimized dismantling to reuse module with high value-added at the lower cost.

In 2002 Lambert introduced the concept of "incomplete disassembly" [14] justified by certain technical constraints: irreversible connections and economic constraints since the costs of dismantling are inversely proportional to the profits generated by the reuse of the disassembled components. Using CAD software, one can determine if dismantling one part is blocked by another part. A new research field in design emerged in response to the need for making dismantling profitable: "Design for Modularity". The modularization of products is the first step for sustainable design [18]. Modular products make it possible to improve valorization of materials by differentiating the modules which can be recycled from the modules which cannot be recycled [19]. The design of future products must reflect the definition of the modules and architecture.

The majority of products on the market today do not have clearly defined modules, complicating the evaluation of end-of-life scenarios. In products that have a great number of components, sub-units can be gathered, corresponding to functional groups of the product (washing machine case study [16]).

Modular decomposition is a means of optimizing dismantling and making environmental and financial gains.

Remanufacturing allows reusing products or modules in several phases according to customer requirements or market evolution (e.g. updating computers systems) [18]. Tomiyama proposes a concept, "Post Mass Paradigm Production" [20] to reduce the consumption of natural resources as well as the production of waste while maintaining the standard of living at current or higher levels. The satisfaction of this new model passes by an increase of products lifetime, posing the problem of functional obsolescence. The increase in the product's period of utilization and thus the limitation of obsolescence incorporate a specific strategy according to the value of the component (repair, update, reuse, etc.) "Longer-life products should have functional upgradability besides reliability and fault-tolerance" [21] [22].

One of the aspects least discussed in the literature is the benefit of integrating the modular approach into the life cycle of the product. This would allow designers and managers to evaluate the product not only through one life cycle but through several use cycles of the modules. The product is then seen not as the result of a material assembly and manufacturing process but as the sum of interconnected modules that will become central units of the model construction. Alexis Gehin [10], whose work reflects this approach, proposed (brick of life cycle) developing a product model using the strategies of revalorization of the components in several use cycles. His approach allows an environmental evaluation of a product according to these modules, but considering several use cycles imposes operational costs (Supply chain, refurbishing, etc).

Few papers report on how systems whose components are reused beyond two use cycles perform: environmental impact and economic costs according to strategies of modules life cycle. Although remanufacturing is a sustainable strategy of end-of-life, there must be a link between current and future products.

This article attempts to define the optimal lifecycle of a product for redesign from a modular point of view and Multiples Life Cycles (MLC) by respecting the 3 pillars of sustainable development.

## 3 EVALUATION METHOD FOR END-OF-LIFE OF REMANUFACTURABLE PRODUCTS

The originality of this article lies not in examining consider the environmental and economic impact of the product through its life cycle but to extend the evaluation through several life cycles of the modules. We do this by concentrating on the reuse of the modules. For consumer goods, reusing modules provides a theoretical environmental profit but in the industrial world companies encounter many constraints: technical, functional and economic.

### 3.1 Optimization of product architecture

The design of most consumer goods is based on architectures that marginally involve environmental problems. Electronic products, for example, have components that incorporate great material diversity (ferrous materials or not, plastic materials, glass, etc) and are connected by varied joint types (clips, screws of different diameters, sticks, spring retaining rings, rivets, etc). With the introduction of the WEEE Directive, the disassembly process became a requirement for recycling (separation of the materials mixtures) or remanufacturing components. The current and future rates of valorization specified in the directive generate additional financial costs. These new requirements made emerge new tools in engineering of the life cycle. Among these tools, software such as ProdTect® [23] or EIME (adapted to the study of the electronic print board [24]) enables managers, based on certain parameters of design (joint types, direction of dismantling, materials, manufacturing processes, etc.) to know the dismantling times (and costs) and the rates of recycling. Product structure knowledge is a prerequisite for using these tools, thus limiting the use of these tools in the downstream stage of design. The designers input the properties of components (materials, shape, dimension, orientation, etc), the connections between components, and the priorities (the relations of anteriority between two components to define the sequence of dismantling). The software determines the level of dismantling from minimal costs to optimal rate of valorization. The product is evaluated according to a specific scenario.

The time for disassembling is an important criterion in the construction of end-of-life scenario. A component with high value-added can require the integral disassembling of the product, which may lead to crippling economic costs.

The tools available for optimization of product architecture, such as ProdTect® and LCA tools are very complementary. ProdTect makes it possible to design a dismountable product while LCA makes it possible to design an optimal end-of-life scenario by measuring recycling rates to satisfy regulations and optimize costs.

### 3.2 The concept of modularity

The business-to-business literature documents many examples of companies that are successful with modularity, including Xerox [25], baby prams [12] and Velo'v [26], all inspired by the concept of Product Service System (PSS). However in small household appliances (B2C market) it is difficult to follow these examples without falling into the second-hand market. The small household appliances currently on the market are not optimized for remanufacturing. Certain parts can be technically reused but the installation of reverse logistics and the associated costs constitute a major stumbling block. Modularity can help to overcome these obstacles. Design for Modularity consists in designing elements of the product (the modules) to carry out some function satisfying customers' needs and being removable [27]. A modular concept makes it possible to reduce the number of interactions among modules. It is necessary to determine, a priori, the modules which must respect certain criteria (price of the components, functionality, lifetimes, etc.). The difficulty lies in defining the borders of a module, knowing that the preexisting modularity in the product is only the reflection of the aptitude for the assembly or maintenance. In this paper we regard a module as an assembly of components achieving a specific function.

To define a module, it is necessary to gather components of the product according to certain criteria. The literature discusses these criteria at length (Table 1). The idea is to gather the components having similar characteristics (e.g. ease of repair [19] [28]) in order to simplify the process of end-of-life [29].

*Table 1. Modules characterization*

| End of Life Strategy [29] | Modules properties [28] | Modules properties [19] |
|---|---|---|
| RECYCLING | Pollutive materials<br>Easy recyclable | |
| MAINTENANCE | Quality: Separate testing<br>Maintenance: Service and repair | Ease of quality insurance<br>Ease of cleaning - to repair - testing |
| REUSE | Carry over<br>Technology evolution | Long life<br>Technology Stability |
| UPGRADING | Upgrading planned | Functional upgradability |

Among the obstacles in remanufacturing are the additional costs incurred to achieve essential quality (according to the definition of remanufacturing) and costs for the reverse supply chain (RSC). The logistics costs associated with product returns and the transport of the modules can be optimized in the design of modules. Components from the same supplier can be aggregated to reduce the distances of the reverse supply chain.

### 3.3 Modular vision of life cycle

In most of the case the electronic products have one value lifetime much less important than their physical lifetime, the main cause being the obsolescence of a component or a module including the components whose technology develops quickly (for example the computer material). This paper shows that it is difficult to remanufacture a machine completely because its lifetime depends on the most fragile components. But these are the components that become obsolescent fastest or they house components that deteriorate quickly. Except for non-reusable modules, modules that are less sensitive to technical or appearance changes, or are more reliable, can be reused to manufacture identical new machines or more advanced machines.

When a product ceases to be functional, it is either discarded or recovered by the manufacturer, who must manage its end-of-life in accordance with regulations that require the product to be incinerated (energy recovery), recycled or reused. With the last process, the functional components are not destroyed but reused through as many cycles as possible. Thus, if a product becomes nonfunctional or obsolete after five years but has a component that is good for 20 years, this component could be reused three times. We talk about modular life cycle because in this vision the module is an individual product, independent of the product in which it is inserted. The life cycle of modules integrates stages of refurbishing: disassembling, cleaning, repair, test, and reassembly [5], which always creates additional costs and environmental loads. To determine the best compromise, we need to simulate various scenarios while varying the lifetime of the modules as well as the number of cycles and the lifetime of the product. This approach is built on a judicious parameter-setting of the system product-modules and their life cycles.

### 3.4 Design parameters for the end-of-life of reusable products

Most consumer goods today are designed in keeping with environmental standards imposed by governments. LCA methods are used to evaluate products in the last phases of design, reducing the designer's freedom. Remanufacturing involves many factors: the product and component lifetimes, the number of reusable components and the "remanufacturing process" [8] inspection, cleaning, disassembly, storage, repair, reassembly, and testing. Each one of these operations imposes design constraints that involve the ease of identification, checking, handling, access, stacking, and separation, among others.

We make several assumptions about the composition of reusable modules to evaluate the performance of existing products. We define virtual modules (modules gathering of the components checking the criteria of classification section 2.2) to carry out the environmental evaluation of end-of-life for the remanufacturing scenario. According to these criteria, the modules can be recycled, reused or upgraded (figure. 1). The upgrade can be regarded as reuse for modules whose technology evolved slightly, thus adding value to the product by changing only one component. This occurs often in the business-to-business market where the obsolete components are replaced by more powerful or more functional ones. The objective is to maximize remanufacturing.

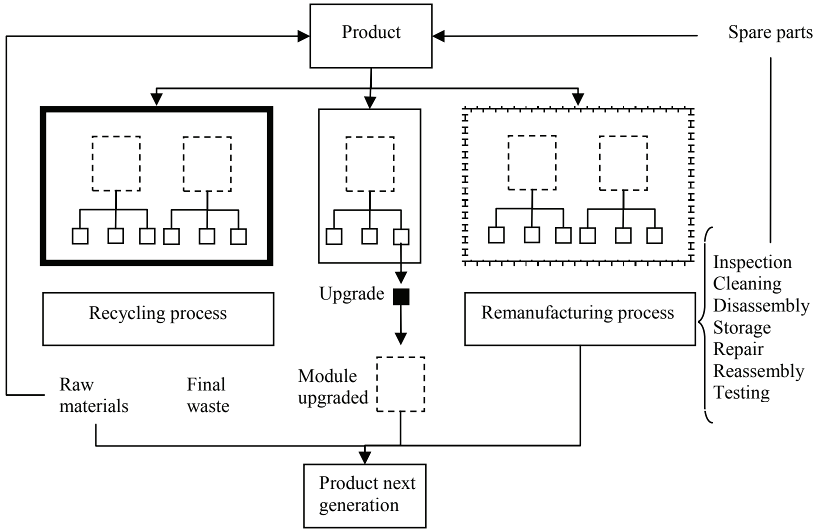

*Figure 1. End of Life for closed loop manufacturing*

To define the parameters, we first evaluate the different scenarios. The product lifetime constitutes one parameter because it influences the functional unit. Then we decompose the product into modules according to the criteria in section 2.2, where each module is defined by a parameter. The last parameter is the number of life cycles feasible for a particular module, which corresponds to the number of times a module can be reused in the manufacture of another product.

*Table 2. End of Life for closed loop manufacturing*

| Parameters | Input dated |
|---|---|
| N | Value time (years) |
| $M_n$ | Module n remanufactured |
| $Z_n$ | Number of life cycle of module n (X times) |

With the three parameters included in Table 2, as well as data on usage (electricity consumption, consumable) we obtains a number of products according to $Z_n$, a logistic scenario, end-of-life scenario (with various recycling rates, re-use, incineration, landfill)

## 3.5 Methodology: Multiples life cycle analyzes

The model can be constructed with LCA software such as Simapro®. We assume that $Z1 = \ldots = Zn =$ constant in order to simplified the comprehension.

### *3.5.1 Construction of the model*

We look at the life cycle not a from product viewpoint but from the view of the modules that constitute the entire product. We model not just one but a series of products depending on the number of modules life cycles. Modeling the product is carried out as if it were an “Empty box” to which we add the modules in order of their lifetime. If Z is the possible number of times the module can be reused during the product life cycle, then, in order to evaluate the impact of remanufacturing the module we have to analyze Z machines. Among these machines, the first corresponds to a completely new product without use of recycled materials or reused modules.  Z-1 remaining machines will be “Empty box” to which we would add the remanufactured modules (Figure. 2).

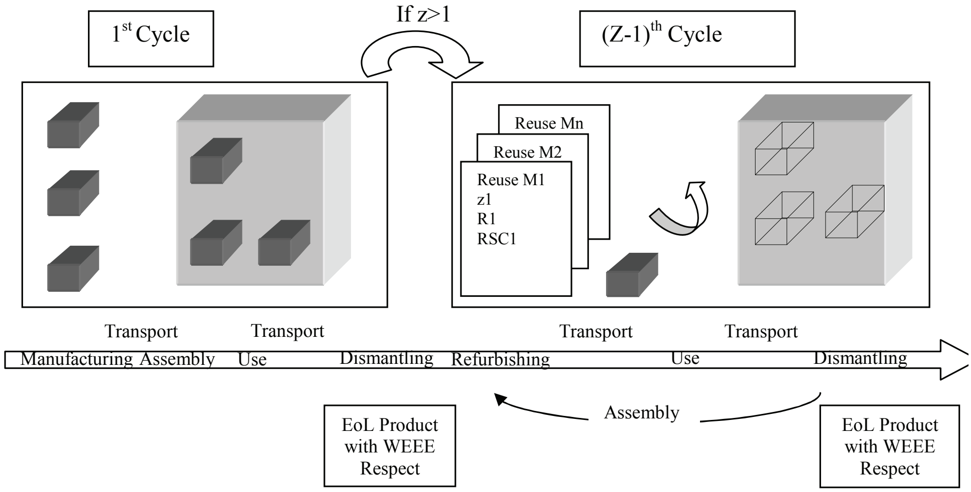

*Figure 2. Construction of Multiple Life Cycles (MLC)*

Depending on the composition of the machines in recoverable modules, the end-of-life scenario will be different. For example, the material rate can be recycled and modules can be refurbished. The type of remanufacturing imposes other constraints which we must integrate using new parameters. Product disassembly outside an assembly center brings additional distances as well as transportation costs to collect products when they are discarded at the end of life. These modules must then be repaired (refurbished). By using the parameters RSC (Reverse Supply Chain) and R (Refurbishing) we can extend the simulation for a more realistic vision of the life cycle.

### *3.5.2 Functional unit for multiple life cycles.*

The definition of the functional unit [9] is fundamental, especially in this parametric modeling. Indeed, while varying N and Z we modify the Functional Unit (FU), but to compare the various life cycle scenarios resulting from a choice of different parameters it is necessary to define an adequate functional unit in this type of evaluation. The idea is to bring back FU to a functional constant (FC) calculus. To obtain an Environmental Score for a MLC scenario ($EnS_{MLC}$) we propose to convert the environmental impact (EI) of each stage by its annual impact.

Environmental score calculation:

$$EnS_{MLC} = \frac{\sum_i EI_{stage\,i}(t)}{N \times Z} \tag{1}$$

i: manufacturing stage, transport stage, use stage, EoL stage…

### *3.5.3 Framework.*

The performance evaluation of a product through several cycles of use requires using several tools together (LCA, ProdTect, Economic assessment).

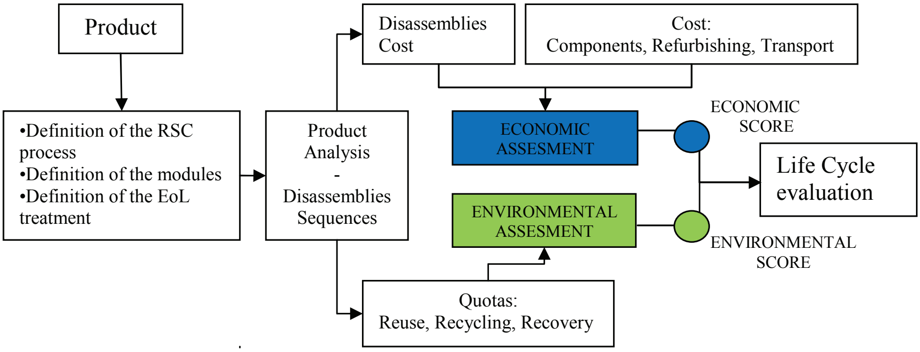

*Figure 3. Framework overview*

For each product component we must know its failure rate, price, lifetime, and technical stability. Then, according to the criteria of modularity (section 3.2), we establish modular groupings. The description of the product must reflect realistic scenarios, particularly for the choice of reusable modules and the process of refurbishing. The modules (potentially reusable) are used to simulate several disassembling sequences according to various scenarios. Product analysis software will model these disassembling sequences so we can determine the time and cost necessary to recover all modules for one scenario. In addition to disassembly costs, the software lets us validate the coherence of the scenarios. The second part of the approach, based on the parameter setting of the life cycle (section 3.4), allows us to evaluate systematically the life cycle of a product according to the number of modules life cycle Z and the product lifetime N. The designer builds the product using the Bill of Materials (BOM) in the following way: part-process, component-process, module-process and finally product-process, which requires a database (Ecoinvent, Buwal, Idemat). The designer then builds the product life cycle by considering all parameters necessary to simulate several cycles of use: usage (energy consumption: Cx), lifetime of the product N, the modules the designer chooses to reuse in the following cycle $M_n$, the number of cycles of reused modules: Z, the scenario of refurbishing (according to the modules) R, logistic scenario: RSC…
The designer can use a “graphic” interface directly connected to LCA software using Macro Excel.

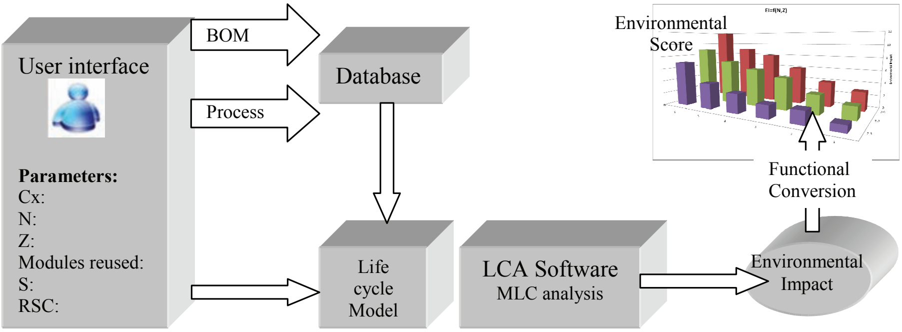

*Figure 4. Framework analyzes environmental*

We conduct an economic study (figure. 3) concurrently. At the end, according to the choices of the designer, we will have a performance evaluation (environmental and economic). The results are in the form of 3D histograms allowing a quick analysis of the results.

## 4 CASE STUDY: MACHINES EXPRESSO

To validate this approach, we apply it to an industrial case study, the espresso maker. They have become quite popular over the past two decades, especially with the introduction of premeasured doses of coffee. With the popularity of the espresso maker has come strong competition from a number of manufacturers. We selected three machines for our study with different technologies: a manual espresso machine and two machines with automated doses.

### 4.1 Perimeter of study.

LCA study has been limited to the environmental impacts related to MLC in extraction-manufacture-distribution use and end-of-life of the machines.

We looked at the influence of the MLC depending on usage: doses or not, sleep mode or not…

Protocol:

1. MLC evaluation: variation of the factors M, $N_R$ and Z.
2. Evaluation Use 1: impact of the doses on the environmental performance.
3. Evaluation Use 2: Impact of electricity consumption on the environmental performance.

### 4.2 Modular decomposition.

We applied our experimental approach to three espresso machines:

- Product A ($P_A$): manual machine without doses
- Product B ($P_B$): manual machine with doses
- Product C ($P_C$): automatic machine with doses

Before beginning to evaluate the three different machines, we must define their modules:

The pumps and the boilers are technologically very similar for all three. But the machines are dissociated by a "quite different infuser module" because their technology (patented) makes it possible to dissociate competitors. The three modules meet the criteria for remanufacturing (section 3.2):

- The vibrating pumps have a greater lifetime (because of short cycles), a greater technological stability (over the past 20 years the pumps of espresso machines evolved slowly).
- The boiler is a central element of the system that often determines the lifetime of the machine (its breakdown generally leads to discarding the machine) because of its high value, descaling seems to be an environmentally and economically interesting option.
- The infuser meets the criteria of fast dismantling with a simple cleaning.

The espresso machine is a straightforward case study because it has only three modules that are potentially reusable, thus limiting the number of possible combinations for experimentation. Our approach must give us the information to decide on the modular grouping that is economically and environmentally advantageous.

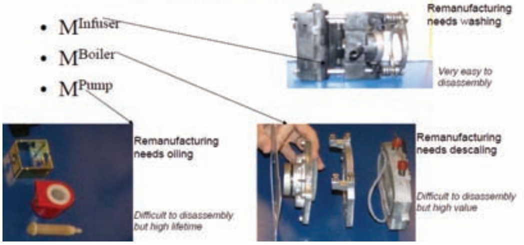

*Figure 5. Modules characteristics*

To simplify the calculations we limit ourselves to analyzing four scenarios:

- WEEE scenario currently recommended by WEEE directive.
- Reuse of the infuser
- Reuse of the infuser and the boiler.
- Reuse of the infuser, the boiler and the pump.

### 4.3 Economic assessment.

For each scenario we calculated the cost of the modules at the end-of-use cycle, including transportation, storage and treatment of end-of-life.

Global cost calculations:

$$C_{global} = C_{tps} + C_w + C_t \qquad (2)$$

$C_{tps}$: transport cost for ton/km: 0.4 € for one lorry of 20t.

$C_w$: warehousing cost

- For 1m3 in/2€;
- For 1m3 off/2€;
- For 1m3 stocked during one day, 0.6 €.

$C_t$: treatment cost

According to the Prodtect® report, we assume that treatment costs include dismantling and recycling with resale of materials.
Because the machine is transported to the production center in its original state, the transport and warehousing costs are not influenced by the number of modules to be remanufactured, but only by the treatment costs, which vary from one scenario to another.

*Table 3. Remanufacturing cost for each scenario*

| Scenario | Transport cost | Warehousing cost | Treatment cost | Global cost |
|---|---|---|---|---|
| WEEE | 0.412 | 0.19 | 4.84 | 5.442 |
| 1 module | 0.43 | 0.27 | 3.99 | 4.69 |
| 2 modules | 0.51 | 0.27 | 3.28 | 4.06 |
| 3 modules | 0.56 | 0.27 | 3.71 | 4.54 |

- $C_{infusion\ system}$ : Supply cost of a new modules “Infusion system” = 3 €
- $C_{boiler}$ : Supply cost of a new module “boiler” = 5 €
- $C_{pump}$ : Supply cost of a new module “pump” = 4 €

Economic score calculation:

$$EcS_{MLC} = Z \times C_{global} - \sum_j (Z-1) \times C_{modules\ j} \qquad (3)$$

j = Infusion system, boiler and pump.

### 4.4 Environmental assessment.

Concurrently with the economic assessment, we conduct a Life Cycle Assessment for each configuration (reused modules, number of cycle of use, lifetime…) to determine an Environmental Score according to the formula (1) in section 3.5.2.
For each of four scenarios we vary the number of cycles, Z, for one lifetime and keeping N constant, we perform the operation again until N=5. Three cycles of use suffice because beyond three the technological rupture would be too large. Depending on the compatibility of the module with the architecture of the new product, we may opt to consider any upgrades.

*Table 4. Environmental & economic assessment for product C with 3 modules reused*

| P=NxZ | N | Z | EI | EnS | EcS |
|---|---|---|---|---|---|
| 1 | 1 | 1 | 3.49 | 3.49 | 4.54 |
| 2 | 1 | 2 | 3.8 | 1.90 | -2.92 |
| 3 | 1 | 3 | 4.13 | 1.38 | -10.38 |
| 2 | 2 | 1 | 3.9 | 1.95 | 4.54 |
| 4 | 2 | 2 | 4.63 | 1.16 | -2.92 |
| 6 | 2 | 3 | 5.35 | 0.89 | -10.38 |
| 3 | 3 | 1 | 4.32 | 1.44 | 4.54 |
| 6 | 3 | 2 | 5.46 | 0.91 | -2.92 |
| 9 | 3 | 3 | 6.59 | 0.73 | -10.38 |
| 4 | 4 | 1 | 7.73 | 1.93 | 4.54 |
| 8 | 4 | 2 | 6.29 | 0.79 | -2.92 |
| 12 | 4 | 3 | 7.84 | 0.66 | -10.38 |
| 5 | 5 | 1 | 8.86 | 1.77 | 4.54 |
| 10 | 5 | 2 | 7.13 | 0.71 | -2.92 |
| 15 | 5 | 3 | 9.09 | 0.60 | -10.38 |

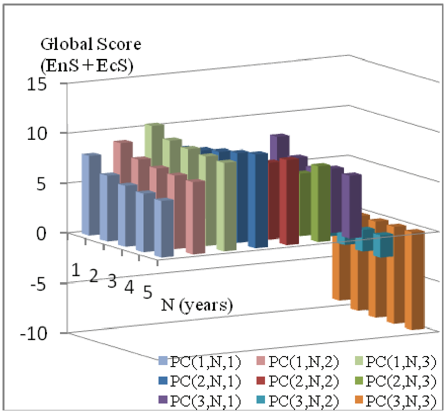

*Figure 6. Simulation for one product*

### 4.5 Results and interpretation.

For each of the three espresso machines we present the results in three separate diagrams (Figure 6) where each section shows the aggregate environmental score and an economic score corresponding to the economic costs generated by the remanufacturing.

Each simulated configuration is represented by a point $P_A(M, N, Z)$ positioned in a Cartesian chart corresponding to its economic costs and its environmental impact (Figure 7). ($P_A$ representes product 1, M the number of reused modules, N product lifetime and Z the number of cycles).

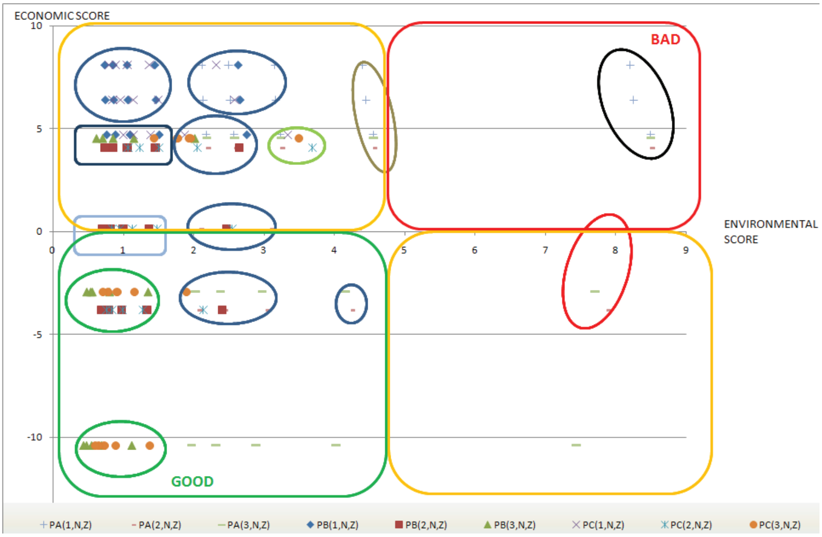

*Figure 7. MLC selection chart for Espresso machine*

This graph shows that some products have greater impact or are more expensive than others. The most salient point, however, is the groupings of product configurations we can make. By displaying the results in this form, a designer can select a modular arrangement from a large array of configurations (choice of reusable modules, modules life cycles, product lifetime, etc.).

Although we used competing products for this case study, the goal is to use this approach in the design phase. The impacts of the products are not only related to their Extraction-Manufacture and End-of-life phases influenced by remanufacturing but, as in the case of the espresso machines, the use phase accounts for approximately 90 percent of the environmental impact. This is due mainly to the use of doses and the electricity consumed by the machine even in sleep mode.

*Table 5. Distribution of Environmental impact: Produit C (3,5,3)*

| Manufacture & EoL | Use | | | |
|---|---|---|---|---|
| Machine $P_C(3,5,3)$ | Doses | | Electric Consumption | |
| | Landfill | recycling | Sleep mode | No Sleep mode |
| 5% | 92,3% | | 5,3% | |
| 7% | | 89,2% | 7,4% | |
| 6,3% | | 80,7% | | 16,3% |
| 4,6% | 85,5% | | | 12,1% |

*Table 6. Distribution of Environmental impact: Produit C (3.WEEE)*

| Manufacture & EoL | Use | | | |
|---|---|---|---|---|
| Machine $P_C(3.WEEE)$ | Doses | | Electric Consumption | |
| | Landfill | Recycling | Sleep mode | No Sleep mode |
| 9,2% | 87,8% | | 5% | |
| 12,6% | | 83,5% | 6,9% | |
| 11,4% | | 76% | | 15,4% |
| 8,6% | 81,8% | | | 11,5% |

A comparison between the MLC scenario and WEEE scenario shows that the impact of the manufacture phase decreases by about five percent with the remanufacturing of the three modules. On these types of products the use of consumable masks the performance.

## 5 CONCLUSION

The development of product life cycles is an important step preceding the design of sustainable products. Designers must decide on life cycles early in the design process. This article suggests that designers evaluate several concepts (various arrangements of modules) related to multiples life cycles to account for the environmental and economic performance, two of the three pillars of sustainable development. Integrating this approach into the design process allows us to technically isolate the most powerful systems. We can identify the constraints of treatment at the end-of-life (optimization of disassembly time and module recovery, refurbished modules and reuse in new products) and the level of organizational constraints (logistic costs, environmental regulations, etc.). Product decomposition in modules with several cycles of use for reusable modules has a better environmental and economic performance. In our future research, we plan to apply this method to a business-to-business product in an industrial sector. We also intend to explore customers' needs in products design, a factor currently not addressed in the research.

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