Eco-Maintenance: The Improvement of Environmental Sustainability by Means of Maintenance

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Abstract

Stating the importance attributed to sustainability issues in industrial field, the paper proposes a framework for the assessment of environmental impact of failures and malfunctioning, with the aim to prioritize maintenance activities according to a sustainable perspective. Proposed approach identifies environmental impacts of maintenance and suggests some steps to follow to evaluate the effects of different maintenance scenarios by using Screening Life Cycle Modeling. Effectiveness and applicability of proposed method is tested through an industrial case study of a gas turbine cogeneration system.

Keywords
Environmental sustainability, maintenance strategy, life-cycle modeling, ecodesign

1. Introduction

In recent years sustainability issues assumed an ever increasing importance in industrial manufacturing. Nowadays, customers and other stakeholders are addressing ever more attention to environmental responsibility of organizations and green attributes are becoming competitive weapons [1-3]. In this context, while the role of design [4-6], innovative processes and technologies [7, 8] in greening production activities has been widely discussed, maintenance contribution to prevent and reduce manufacturing environmental impacts seems to be poorly investigated. Nevertheless, depending on the specific situation, factors due to maintenance management, such as leakages of dangerous substances, the increase in natural resources' consumption, energy use and emissions [9] can play an important role for environmental performances of the whole life cycle of an industrial product/service. Then, the characteristic of maintenance plan, strictly related to reliability and safety concerns, certainly influence sustainability of a production process, affecting its efficiency both in terms of technical and environmental performances. On these considerations, the paper proposes a framework for the improvement of environmental sustainability by means of maintenance. The main objective of the developed method is to increase system sustainability by the adoption of an eco-maintenance strategy, which improves environmental performance throughout the life cycle of the system. In details, the paper is organized as follows. In section 2 the general background where the research work is set is presented; concepts and approaches used for the development of the eco-maintenance framework are presented in section 3. The methodology was applied to a case study, i.e. the improvement of environmental performances of a gas turbine: achieved improvements were further tested through a simulation analysis presented in section 4.In the end, discussion and conclusions are provided in section 5.

2. Maintenance for Environmental Sustainability

Very few examples of studies which investigate the relationship between maintenance and environmental sustainability can be found in literature, and most of them are more oriented to the overall optimization of assembling/disassembling processes [10-13]. Other aspects considered are the opportunity to extend product life span [14], to reduce the risk of accidents with environmental consequences [15], to improve equipment and process efficiency [16] and to adopt specific maintenance strategies in order to increase the number of reusable components, thus reducing the environmental impact of product's end of life [17]. Whether the importance of proper maintenance in green manufacturing is addressed [18], evaluation methods are not provided. Then, there is a lack of specific widespread tools at engineers' disposal for the assessment of the whole environmental impact associated to failures and malfunctioning. Considering negative effects of poor maintenance on production sustainability, Raouf (in [19]) defines the environmental impact associated to improper maintenance, as shown in Figure 1. Overproduction and over processing due to breakdowns determine the use of more raw materials and energy to produce unnecessary products which can become obsolete, thus increasing emissions and waste. Extra-inventory, indispensable to mitigate the effects of breakdowns, and defects caused by malfunctioning are responsible for damaged and obsolete work-in-progress products, which increase again the quantity of raw materials used. As for production, extra-transportation has a very negative effect on the environment: it produces more energy consumption and emissions together with more packaging required to protect products during movement. The last aspect considered is maintenance delay. Wasted energy from heating, cooling and lighting during production downtime is the main consequence of waiting for maintenance.

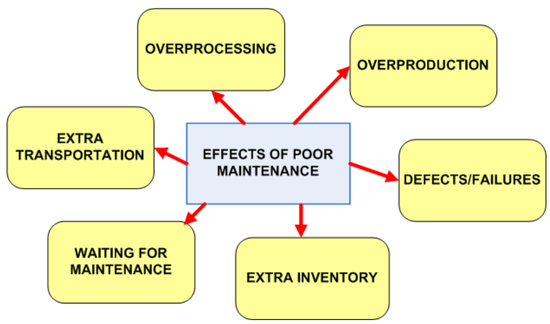

Figure 1: Effects of poor maintenance to the environment [19]

Raouf's framework is focused on production process and its environment, without taking into consideration the extended environment and time horizon characteristic of system's life-cycle. To overcome this limitation, another interesting approach is the 6Rs one, which analyses the role that maintenance activities play in each phase of system's life-cycle, including design and development activities. According to this pattern, proper maintenance can reduce material and energy consumption, as well as waste and pollution by preventing breakdowns and keeping the equipment's efficiency at a high level. Adequate maintenance can also increase the quantity of material which can be recovered or recycled, given that components are replaced before catastrophic failures. While reuse of old equipment and components is increased by maintenance activities, the redesign and remanufacturing of new items can be decreased by augmenting assets' life-span (see Figure 2). Given that the environmental sustainability concept concerns the life-cycle of a product/service, the latter approach was used to develop the eco-maintenance management framework described in the following section. In fact, maintenance is one of major services associated with product life cycle management [20], as it monitors changes in system conditions due to deterioration, providing the required functionality during its whole life cycle.

3. Eco-maintenance Framework

As mentioned before, even though a large number of research works have been carried out on maintenance intended as a whole, they rarely focus on the specific ambit of environmental sustainability, or they concern only a particular type of systems. Thus, stating the lack of specific methodologies, the research work focused its attention on the integration of well-known methods and techniques of the Ecodesign field together with maintenance management issues. With the aim of developing a framework of a general nature, which could be used for the assessment and the improvement of maintenance activities from an environmental perspective, i.e. from what we called "eco-maintenance", the use of ecodesign tools was foreseen in synergy with other methods which do not directly concern environmental performances of a system, but analyze other properties which might affect its environmental sustainability. Some examples can be provided considering system reliability, which affects: life-span of a product; resources used in repairing, cleaning, refurbishing; losses caused by unexpected failures and downtime periods; etc. All these aspects play a significant role in the life cycle of the system in terms of both environmental and financial loads. At the same time, a proper management of the system life-cycle can allow the achievement of beneficial effects on the environment, especially by optimizing those life cycle phases during which the system is managed by the customer (i.e. use phase, end of life phase).

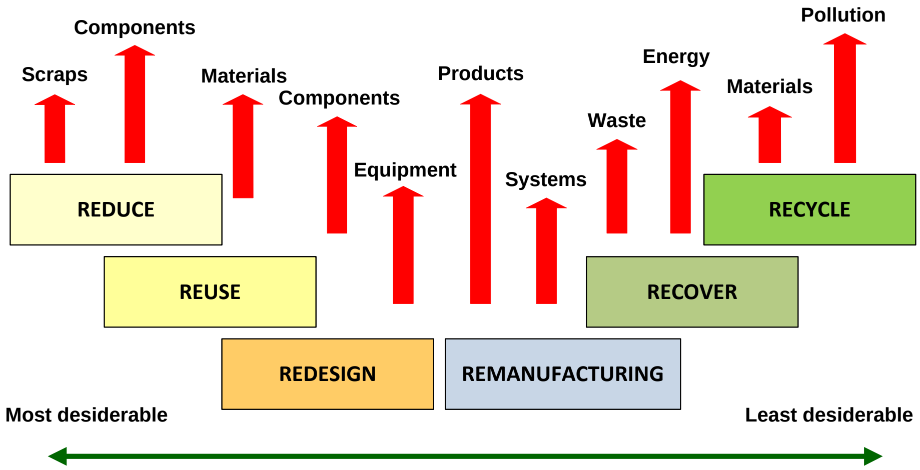

Figure 2: 6Rs approach to maintenance for environmental sustainability

For these reasons, the proposed framework (summarized in Figure 3) is based on a process (eco-maintenance strategy) divided in four main steps that could help engineers to merge maintenance management activities with life cycle management issues. In particular, a systematic process was developed, that is aimed at making it easier to find optimal maintenance plans for the system. Actually, the definition of a good framework certainly helps engineers in following a systematic and rational process, that allows them to avoid neglecting or underestimating environmental aspects in the definition of the system maintenance characteristics. Such a process is characterized by the following criteria:

- Subdivision of the activities in phases and stages more or less detailed;
- Deployment of the whole process in a systematic and iterative way;
- Introduction of environmental analysis since the beginning of the process.

The process is characterized by an increasing level of detail (following a top-down approach), with the aim of allowing engineers to efficiently focus on most relevant measures. For each phase, several design tools are suggested to support engineers during any activity of the process. In Figure 3 only the following ecodesign tools are mentioned:

- Environmental Effects Analysis (EEA);
- Quality and Environment Function Deployment (QEFD);
- Life Cycle Assessment (LCA);
- Ecodesign PILOT;
- Screening Life Cycle Modelling (SLCM);
- Quality Function Deployment for Environment (QFDE).

Nevertheless, also other tools should be used, depending on the specific case engineers have to face to.
Main characteristics of the ecodesign tools mentioned in Figure 3.

Environmental Effect Analysis (EEA)

Based on the general framework of the FMEA/FMECA method [21], the Environmental Effect Analysis method [22] is aimed at identifying and evaluating most significant environmental impacts related with a product since the initial stages of its development. The general framework of the EEA method was developed using a similar approach to the one applied in traditional Life Cycle Assessment technique, i.e. goal and scope definition; inventory analysis which considers the whole life cycle of the product; etc. The strength of the method is represented by the evaluation step, which is carried out using different qualitative techniques depending on the designer needs, which brings to light the environmental impacts caused by the product as and the possible interventions to reduce them. Such a qualitative estimation is based on the use of a series of checklists, quite similar to the ones used for the application of the FMEA method, which can be differentiated by means of different criteria for the evaluation, such as the KEE, SIO, and ULF methods, also described in [22]. In all cases the aim is to estimate the Environmental Priority Number (EPR): EPR's higher values correspond to higher impact on the environment.

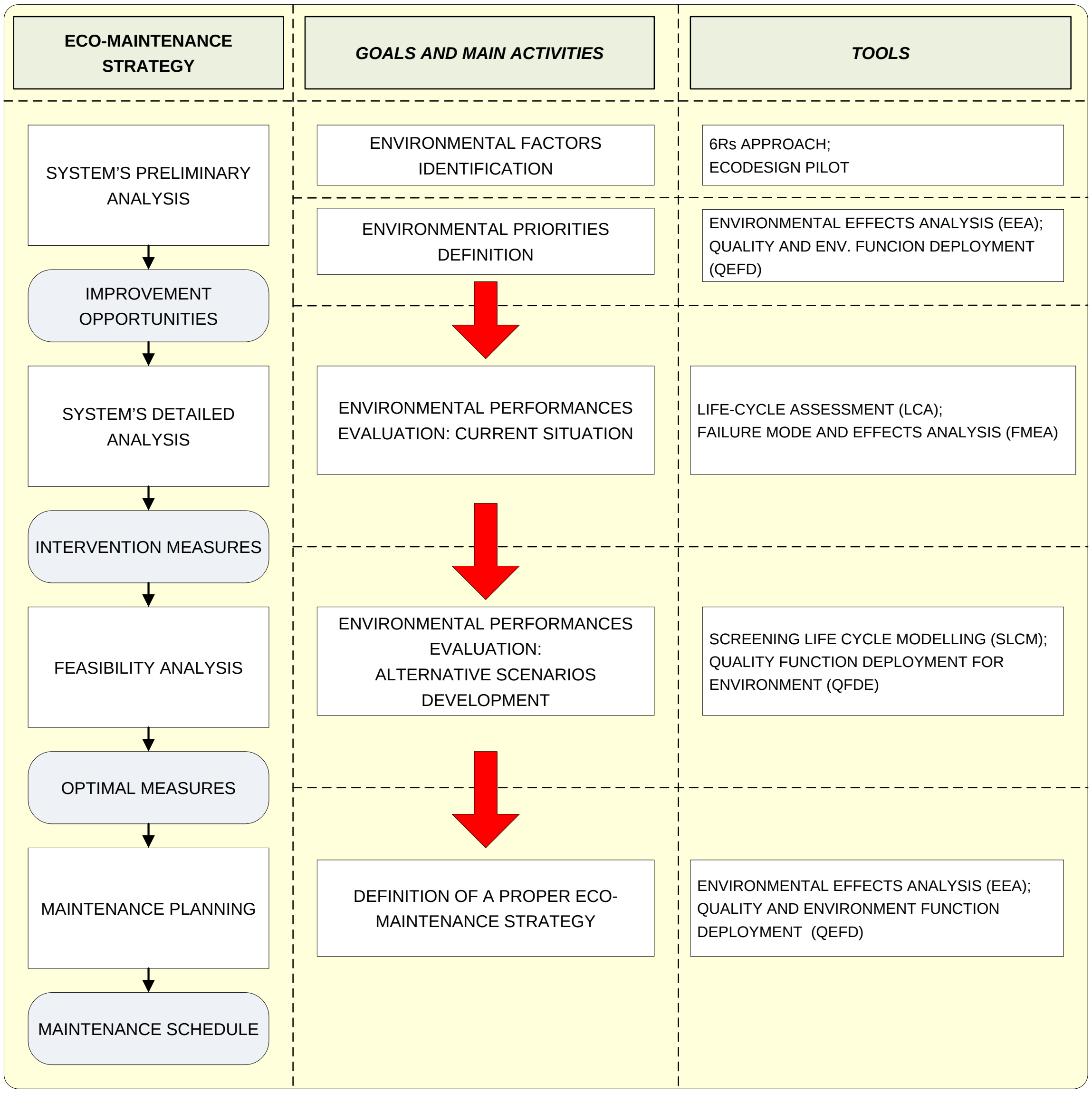

Figure 3: General framework of proposed methodology

Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) is a well-known method which allows the measurement of environmental impacts of a product/service during its whole life cycle, such as: energy consumption, raw material consumption, emissions and other factors. To carry out this kind of analysis there exist different weighting and assessment schemes. Usually the evaluation is done according to standard indicators, i.e. numbers which express the total environmental load of a product. In the paper the adoption of Eco-indicator 99 [23] is suggested as this scheme provides a wide list of indicators and almost all important aspects of industrial production are can be taken into account.

Ecodesign PILOT

The Ecodesign PILOT (Ecodesign Product Investigation Learning and Optimization Tool) method [24] is a technique aimed at evaluating environmental strengths and weaknesses of a product/service by means of the use of a series of checklists structured in different ways depending on the type of product, the product's life cycle and the design phases considered. The goal of PILOT, which is implemented in dedicated software, is the definition of which characteristics most influence the environmental performances of a product/service, taking into account different approaches (e.g. Product Life Cycle, Product Development Strategies, or Product Development Process) related to the nature of the product/service. Even though this method allows the improvement of already existing products and the development of new solutions, the assessment criteria are qualitative, so that results are usually of a general nature. For this reasons, PILOT can be used to draw up the environmental behaviour of a product/service and possible general intervention measure, which can be further developed (if needed) by means of other product development tools.

Use of Quality Function Deployment (QFD) for the environment

Quality Function Deployment (QFD) method [25], which uses a combination of matrices, called "House of Quality", as a tool to investigate and evaluate the relationships between customers' needs and product design parameters explicitly. The use of the method is based on the use a set of matrices (generally called "House of Quality"), where a semi-qualitative assessment of inter-relationships among "whats" (i.e. what customers desire/need), "hows" (i.e. how to satisfy customer needs/desires), and "how muchs" (i.e. the metrics and values of the customers' needs and requirements) can be carried out. Starting from this general framework, the QFD has been adapted to several environmental approaches, with the aim of combining the efficiency of the traditional QFD in the interpretation of customer requirements and translating them into engineering parameters, together with the possibility to analyze the environmental needs concerning the product itself and its life cycle. In particular, we considered the so called "Quality and Environment Function Deployment" (QEFD) method, that following the traditional rules of the QFD, allows engineers to specify in both whats and hows categories environmental aspects related to the product's life cycle [26, 27]. Then, QEFD allows engineers to translate subjective quality and environmental criteria into objective parameters, which can be estimated and measured. Also the QFDE method [28, 29] constitutes an adaptation of the QFD to environmental issues, but its goal is to compare different alternative solutions by comparing the performances of a product/service (in terms of both environmental and technical/qualitative criteria) when one of its components/aspects is modified. In our methodology the use of both QEFD and QFDE is forseen.

Screening Life Cycle Modelling (SLCM)

The Screening Life Cycle Modelling method can be considered as a tool for augmenting results which can be achieved using the traditional life cycle assessment techniques by means of drawing up the possible scenarios of the production/usage of the product over the life span of a single item. In other words, the SLCM allows engineers to estimate main environmental impacts related with a product life cycle in the initial stages of the design process, providing at the same time options for the product's improvement by means of the development of a series of alternative life cycle models [30]. Starting from traditional LCA results, which can be considered as "static" information (i.e. the environmental burdens of a single product during its life cycle phases), the development of life cycle scenarios brings to light the environmental behaviour of the product/service for the whole period it is used/purchased, even though in such a time-framework more than one physical products are purchased/put on the market. In this way it is possible to collect "dynamic" environmental information related to the use of the product/service. The integration of technical issues and product flow management, which enable the evaluation of the product's environmental performances, can support engineers in estimating the potential benefits of possible environmental improvements and managing the overall product/service development. Needless to say, not all illustrated tools must be used together when applying proposed methodology.

4. Case Study

Eco-maintenance management methodology and its associated activities are described more in details in the case study. With the aim of verifying its effectiveness, proposed methodology was applied to an industrial case study, i.e. a cogeneration system which is currently installed in a frozen food production plant. In particular, the turbine of the cogeneration system was analyzed. Main characteristics of the gas turbine are: power of 5,7 MW; working gas: methane; heat rate: 11.400 kJ/kWe·hr; efficiency: 31,5%; life-span: 15 years; fuel consumption: 297 g/kWh. Needless to say, cogeneration is itself a sustainable technology as the contemporary production of steam and power requires fewer natural resources than the production of electrical energy from traditional sources. Besides, system malfunctioning or failure determines the use of electricity from the external electrical distribution network, thus increasing CO_2 emissions. At the same time, also other activities related to system malfunctioning have a relevant environmental impact, such as corrective maintenance, manufacturing and installation of new components, etc. On these considerations, it seems rather clear that preventive maintenance, by increasing system availability, plays an important role in improving environmental performances. In the following paragraphs the different phases of the methodology applied to this case study are illustrated, starting from the preliminary analysis, which involved the use of Ecodesign PILOT and EEA methods. Then, for the detailed analysis of the system the life cycle assessment was carried out by means of the Eco-indicator 99 method; results of this analysis were used to perform the feasibility study applying the SLCM method..

4.1 Preliminary analysis

The first step of the methodology consists in the definition of what we call "maintenance environmental factors", which represent failures' negative consequences to the environment. Starting from the 6R approach presented in section 2, and considering the objectives of Ecodesign PILOT, declined according to a maintenance perspective, factors considered in the case study were:

- increase in the use of resources (natural ones, energy, raw materials, etc.) due to malfunctioning components;
- production of scraps and waste due to failures;
- air emissions and water pollution due to failed monitoring systems and leakages caused by breakdowns;
- life span increase: maintenance activities can increase equipment and components lifespan and, in some cases, make these items reusable for other scopes.

When considering these factors, also the negative effects of excessive maintenance must be taken into account. As a matter of fact, if it is clear that failures affect system sustainability, it must be outlined that unnecessary replacement during maintenance jobs can be equally damaging to the environment, especially when replaced components are still usable. In a cogeneration plant, the most significant resource is certainly energy. Starts and stops are particularly critical for the gas turbine, sensibly decreasing its efficiency in terms of production and, as already discussed; a breakdown implies the use of conventional systems to obtain electrical and thermal energy. Moreover, the efficiency of the system is strongly related to cleaning and refurbishment activities. Each failure which determines the system stop has the same consequences to production continuity, so as to waste generation. In fact, it is reasonable to assume that as soon as the system blocks, it is immediately by-passed and production continuity is then guaranteed by conventional plants. Consequently, this aspect is not particularly relevant to the evaluation of breakdowns. With respect to the third category, emissions, even if a gas turbine is characterized by low levels of NOx, the methane combustion produces pollutants (nitrous oxides, carbon monoxide and unburned hydrocarbon emissions). These emissions are influenced by combustion temperature; hence failures which determine an inadequate combustion must be prevented. The last category is the life span increase, in which there is only one factor to evaluate: the possibility to enlarge components' lifecycle. This factor is particularly important as the analyzed system is the combination of a wide range of different components, most of them technologically advanced. Reuse and avoid manufacturing of new components are both significant argument in terms of sustainability.

The definition of environmental priorities has been carried out using EEA (section 3). In particular, the KEE-method was selected: it is divided into three parts where product-related environmental demands, ecology and improvement possibilities are taken into consideration. The Environmental demands comes from Customers (k), Internal (i), Authorities (l) and the public (a), each one evaluated according to a specific scale. When considering the case of maintenance, as no direct environmental demands from end products' customers associated to failures are assumable, internal customer (organization) is considered. Then, more general demands, such as the reduction of energy consumption, are concerned when evaluating factor (a). The demands are added and then multiplied by 2, this is to gain balance in regard to the part of ecology where the maximum value is 9. Another aspect taken into account is "ecology", in terms of quantity and seriousness of environmental damage. In Figure 4 the application of the EEA is shown. The analysis took into account a selection of failures: in particular, auxiliary systems were ignored together with components whose failure cannot be prevented. The attention was paid to major inspections, when the majority of components are replaced. According to EEA the most critical failure is associated to nozzles. The reasons for this results depends on the fact that one principal cause of damage to gas turbine combustion components is imbalanced fuel distribution due to dirty or defective fuel nozzles. When more fuel flows to one nozzle and less to another, an increase of NOx and CO emissions takes place because of the existence of hot and cold spots in the combustion section. This effect has a double negative consequence as it also reduces life of liners, turbine nozzles and blades. The analyzed gas turbine has twelve fuel nozzles: in order to avoid the described negative consequences, fuel flow-rate through each nozzle should be uniform and mixing of fuel with air should be equally effective for each nozzle. Cause of non-uniform flows includes fatigue cracks in the nozzle, manufacturing defects, improper assembly, erosion or coke and ash deposits. Excluding manufacturing defects, these problems can be minimized by proper maintenance.

Environmental Effect Analysis - EEA [KEE method]										
Inventory				Valuation						
Life-cycle		*Environmental Characteristics*		*Part1*				*Part2*		EPN= (k+l+i+a)·2+(m·s)
No	Life-cycle Phase	Failure	Envir. Effect / Aspect	k	l	i	a	m	s	
1	OPERATION	Dirty ventilation air filter	System efficiency loss	1	1	0	1	0	2	6
2	OPERATION	Fan bearing wear	System efficiency loss	1	1	0	1	0	2	6
3	OPERATION	Gas filter obstruction	Imperfect combustion, emissions increase, system efficiency loss	2	1	1	2	1	3	15
4	OPERATION	Double cartridge filter obstruction	System efficiency loss	1	1	0	1	1	2	8
5	OPERATION	Compressor oil filter obstruction	System efficiency loss	1	1	0	1	1	2	8
6	OPERATION	Dirty compressor blades	System efficiency loss	2	1	0	1	3	2	14
7	OPERATION	Fuel nozzle failure	Imperfect combustion, emissions increase, system efficiency loss	2	1	1	2	2	3	18
8	OPERATION	Compressor bearings wear	System efficiency loss, domino effect	2	1	0	1	1	2	10
9	OPERATION	Turbine bearings wear	System efficiency loss, domino effect	2	1	0	1	1	2	10
10	OPERATION	Liner wear	Imperfect combustion, emissions increase, system efficiency loss	2	1	1	2	2	3	18
11	OPERATION	Cross fire tube failure	Imperfect combustion, emissions increase, system efficiency loss	2	1	1	2	1	3	15
12	OPERATION	Turning gear wear	System efficiency loss, domino effect	1	1	0	1	2	2	10

Figure 4: Environmental Effects Analysis (excerpt)

4.2 Detailed analysis

Once most critical failures have been outlined, the second stage consists in a detailed analysis of the components to which the higher criticality is associated. In order to assess environmental performances of the system a LCA analysis was carried out using the Eco-indicator 99 method. A scheme of the cogeneration system is in Figure 5. Considering its life cycle and analyzing fuel nozzles, which resulted the most critical components, maintenance jobs affect only the use phase, as production and disposal of the turbine are the same even after nozzles' replacement. Then, LCA is focused on the nozzle, assessing its contribution system's environmental performances. In Table 1 main characteristics of gas turbine system and nozzle used for the application of the LCA method are summarized.

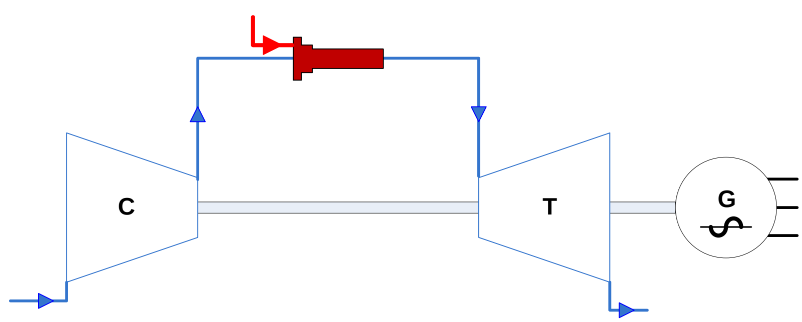

Figure 5: Scheme of the cogeneration system (C = Compressor; T = turbine; G = generator)

Table 1: System characteristics

GAS TURBINE COGENERATION SYSTEM	Working hours per year	7.200
	Efficiency reduction ratio without maintenance	3% / 2.400 hrs
	Number of fuel nozzles	12
	Weight	1 kg
	Material	Steel low alloy
Delivery	Transport by 3,5 tons' van	260 km
Fuel nozzle's packaging	paper	0,3kg

It has to be noted that disposal strategy for both nozzle and packaging is recycling. In Figure 6 LCA results are shown (according to the assessment procedure of the Eco-indicator 99 method, values are expressed in millipoints – mPt [23]). The most critical phase is the production one (Figure 6), hence intervention measures should limit the number of nozzles replacements, which have a relevant environmental impact, but, preserve system efficiency, avoiding emissions' increase.

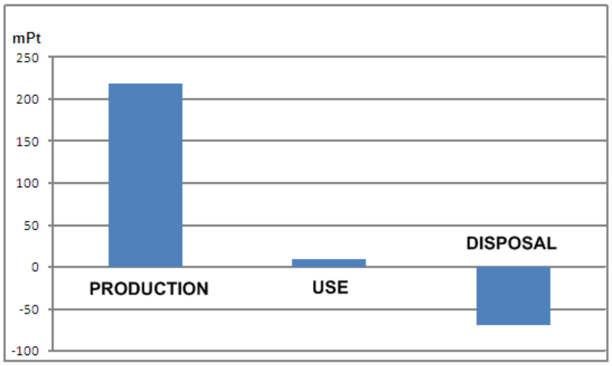

Figure 6: Life cycle assessment of a fuel nozzle (Eco-indicator 99)

4.3 Feasibility analysis
In order to define optimal measures, the Screening Life Cycle Modeling (SLCM) [30] method was applied taking into consideration three possible maintenance actions and evaluating alternative scenarios. More in details, maintenance tasks can be divided in three categories of maintenance jobs:

- M1 (cleaning): nozzles cleaning and, replacement of failed components (1%).
- M2 (refurbishment): a deeper cleaning which restore original fluid- dynamics performances.
- M3 (replacement): nozzles full replacement.

In accordance with the SLCM procedure, a base scenario reflecting current situation was developed together with two alternative solutions for maintenance jobs, with the aim of improving environmental performances of the whole system. Main characteristics of these all three scenarios are summarized in Table 2.

Table 2: Maintenance jobs intervals for each scenario

	M_1	M_2	M_3
Base scenario	1year	----	2 years
Scenario 1	1year	2years	4 years
Scenario 2	6months	1 years	6 years

Based on this, the simulation was carried out considering a 16 year period: in Figure 8 the comparison of the behavior of the three scenarios is shown. It has to be noted that due to production characteristics, the supply of energy needs to be continuous. In case of failures and during maintenance jobs, energy is supplied by the electric transmission network. Such an additional impact was also considered in the simulation.

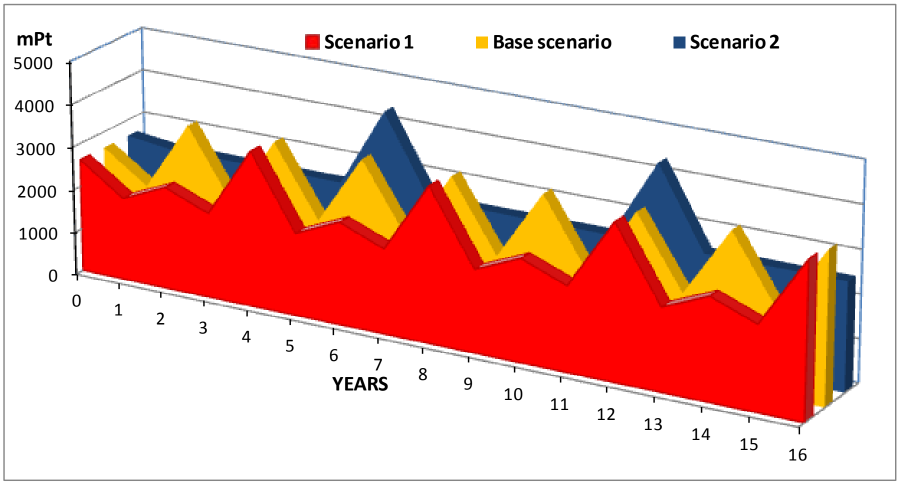

Figure 8: Life cycle models of the three different scenarios

Modeling analysis brought to light that, in accordance to results provided by LCA, Scenario 1 is the most environmentally friendly as it limits the number of replacements, with regard to Base Scenario, without sensibly reducing system efficiency, as in the case of Scenario 2: the overall impact value, estimated during the whole modeling period, is 91,1 % of the Base Scenario (current situation), while Scenario 2 is slightly higher that base model (100,2 %). At the same time, also the fulfillment of production needs was considered, in order to complete the feasibility analysis. Actually, the impact of different scenarios on the efficiency of the energy generation process was analyzed, taking into account the following aspects: domino effect of failures, loss of production, and loss of efficiency. From economic point of view, it also appears clear that scenario 2 is more expensive for the company, because of the higher number of interventions requested. Needless to say, a life cycle costing analysis (LCCA) could provide more detailed information on economic issues.

5. Conclusions

The study was based on the definition of a proper methodology (i.e. the coordinated combination of different product design and management tools) aimed at the improvement of environmental sustainability of a product-system focusing on its maintenance. Effectiveness and applicability of this methodology (Figure 3) were tested through an industrial case study. Results from the analysis shows that maintenance activities sensibly influence (positively or negatively in case of excessive maintenance) environmental sustainability of a system during its whole life cycle. By adopting proposed methodology, weak points of the maintenance plan were identified (by means of the product-system life cycle analysis) and proper corrective measures were suggested thanks to the simulation analysis. According to the developed simulation, the adoption of specific changes in the maintenance plan succeeded in reducing negative effects on the environment. In particular, alternatives were preliminary evaluated according to customers' needs even in terms of environmental sustainability and possible improvements were estimated applying again a simulation approach. Even though a further research work has been already planned in order to perform both a life cycle costing analysis (LCCA), and the application of QFD-based methods, results obtained using the eco-maintenance framework were considered reliable by the company, which has modified maintenance schedule according to the optimized model.

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