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Proposal of a model for Life Cycle Optimization of industrial equipment

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Abstract

Pressure of emergent countries, policy makers and industrial companies' interests are pushing European companies towards a high consideration of whole product life cycle. Designers and systems engineers are the main actors involved, due to their high influence on product life cycle costs and environmental impacts since early design phase.
The aim of the paper is to propose an integrated, structured and robust model, completed by methods / techniques, to support and help the activity of designers and engineers to create and identify the optimal life cycle oriented solution.

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Keywords: Life Cycle Assessment; LCA; Life Cycle Costing; LCC; Life Cycle Optimization; Life Cycle Simulation.

1. Introduction

Sustainable Manufacturing [11] is an emergent and relevant concept for the modern competitiveness at industrial level. It is not only a "fashionable" theme, but a real need to be pursued, and industrial companies are more and more forced to be eco-efficient and to realize green products / systems, keeping a low cost of ownership for their customers. These conditions are necessary to compete in the global market and to gain competitive advantages for the next years. To realize such products / systems, designers and engineers must have a holistic vision of their projects, considering all the lifecycle phases (production, utilization, maintenance, support, dismissal / retirement).

Indeed, during the last years, the operating context, where European companies operate, has been dramatically changed due to several reasons, often mutually related.

First of all, globalization pushed the industrial competition at another level, changing completely the "existing world". Today, competition is global, and the modern world is more and more "flat" [10], with global competitors starting from the same line. In this, European companies are particularly forced to face the low cost pressure from emerging countries, which makes impossible to them a mere price-based strategy.

At the same time, also the customers' behavior changed. Global customers demand for personalized solutions [18], more reliable systems, less polluting equipment, less consuming plants / facilities, greener products, etc. Moreover, environmental consciousness is more and more felt, also due to the imposition of regulations and normative, like the Kyoto protocol, as well as tons of EU Directives (e.g. Waste Electrical and Electronic Equipment Directive, Restriction of Hazardous Substances Directive, etc.).

In general, the society – at least at European level – is looking for a new development model, more sustainable and affordable. In this context, manufacturing companies have to identify the best life cycle oriented solution, in order to satisfy the customers' requests and survive to the global competition. In fact, being able to develop eco-friendly, energy-efficient and green products before the others could give a competitive advantage for the next years.

As previously stated, designers and system engineers are the most involved actors, due to their high influence on life cycle costs and environmental impacts. Indeed, some empirical researches have been conducted to study how much

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costs are fixed during early design phase. Munro [19] estimates that product design represents the 5% of total costs; however it influences the 70% of total. Romm [22] instead argues that when 1% of a project's up-front costs are spent, up to 70% of its lifecycle costs may already be committed, while when 7% is spent, up to 85% of lifecycle costs have been committed. Dowlatshahi [6] states that product design influences between 70% and 80% of the product total cost. Finally, Blanchard [2] argues that development process is the phase where the majority of lifecycle costs are fixed, about 2/3 of the total. The same consideration, about product life cycle environmental impacts, is reported in Rebitzer et al. [21].

The aim of the paper is therefore to propose an integrated, structured and robust model, completed by methods / techniques, to support and help the activity of designers and engineers, in order to create and identify the optimal life cycle oriented solution. Paper is organized as follow: Section 2 illustrates the current state of the art; Section 3 describes the conceptual framework of the model proposed; Section 4 shows first results of the model, applied on a real case; finally, Section 5 concludes the paper.

2. State of the Art

In the previous section life cycle perspective, in term of costs and environmental impacts, is pointed out.

Analyzing the literature, two methodologies were developed during the past years to evaluate costs and environmental impacts generated along the whole lifecycle: Life Cycle Costing (LCC) and Life Cycle Assessment (LCA). Both the methodologies are really well known, being developed by the 60s.

Life Cycle Costing is described as "cradle-to-grave costs summarized as an economic model of evaluating alternatives for equipment and projects" [1]. Elmakis and Lisniaski [8] defined LCC as "the total cost of acquiring and utilizing a system over its entire life span, in other words LCC is the total cost of procurement and ownership". More detailed definitions are proposed by the Society of Automotive Engineers [25] – "Life cycle cost is the total cost of ownership of machinery and equipment, including its cost of acquisition, operation, maintenance, conversion, and/or decommission." – and Landers [17] – "Life cycle costs are summations of cost estimates from inception to disposal for both equipment and projects as determined by an analytical study and estimate of total costs experienced in annual time increments during the project life with consideration for the time value of money".

Life Cycle Assessment is described as "a technique to assess environmental impacts associated with all the stages of a product's life from-cradle-to-grave" [24]. Rebitzer et al. [21] instead stated LCA as "a methodological framework for estimating and assessing the environmental impacts attributable to the life cycle of a product".

The LCA process is a systematic, phased approach and consists of four main phases: goal definition and scoping, inventory analysis, impact assessment and interpretation. This process is described in the "ISO 14040 Environmental Management - Life Cycle Assessment - Principles and Framework" standard [15].

However, the methodologies described above allow only an evaluation / estimation of costs and environmental impacts along the product lifecycle, therefore they result ineffective in the exploration of different alternatives – if it is possible all the ones –, consequently they can't find the best solution.

To pursue this approach, therefore, LCC and LCA methodologies are not sufficient, but it is necessary to apply methods and techniques so as to explore the different alternatives, evaluating costs, environmental impacts and technical performances along the product / system lifecycle.

In literature these methods can be grouped into 2 main areas: optimization and simulation. In optimization area, authors use different optimization methods, in order to optimize costs and / or environmental impacts along the product lifecycle. In simulation area authors use some simulation tools to evaluate costs and / or environmental impacts.

Within our group, two works tried to explore these topics. In Cerri et al. [4], the authors analyzed 79 papers from the last 15 years (39 related to LCC methodology and 40 related to LCA methodology). The objective was to find which types of optimization methods were used and if costs and environmental impacts were together optimized. The contributions are classified in three clusters: (i) simple application of the methodology, (ii) use of software, (iii) optimization. The first cluster considers papers that barely apply the methodology (LCC or LCA). The second cluster includes contributions that use software to calculate costs and / or environmental impacts. The third cluster takes into account papers that optimize product life-cycle's costs and / or environmental impacts.

Focusing only on papers dealing with optimization (11 papers of 79), Linear Programming, Genetic Algorithm and Particle Swarm Optimization were used as optimization methods. Moreover, Genetic Algorithm is resulted the most promising and used. Gitzel and Herbort [13] applied a genetic algorithm to optimize lifecycle costs of a DCS (Distributed Control System), using different GA variants. Hinow and Mevissen [14] used genetic algorithm to optimize lifecycle costs of a substation, improving the maintenance activities. In Kaveh et al. [16] genetic algorithm (NSGA-2) is used to perform a multi-objective optimization of lifecycle costs and initial costs of large steel structures. Furthermore, in this contribution, the strong trade-off between initial costs and lifecycle costs is reported. Frangopol and Liu [9] and Okasha and Frangopol [20] applied a multi-objective genetic algorithm to optimize three different objectives: lifecycle costs, lifetime condition index value and lifetime safety index value for the first contribution; lifecycle costs, minimum redundancy index and maximum probability of failure for the second contribution. The algorithms are applied on structural maintenance. Dufo-Lopez et al. [7] instead applied the Strength Pareto Evolutionary Algorithm (SPEA) to the multi-objective optimization of a stand-alone PV–wind–diesel system with batteries storage. The objectives to be minimized were the levelized cost of energy (LCOE) and the equivalent CO_2 life cycle emissions (LCE).

From this research some interesting points come out: (i) only few papers applied an economic and / or environmental optimization, while the majority applied a simple evaluation, using in some cases software; (ii) only few contributions combine both economic and environmental evaluation and (iii) in multi-objective optimization there is not a unique solution, obviously, but a set of optimal solutions, due to the trade-offs incurred between the different objectives. Therefore the decision makers have to choose the best solution for their customers within the optimal set.

Another literature analysis is related to simulation area. Garetti et al. [12] analyzed the state of the art of the so-called Life Cycle Simulation (LCS). 43 contributions from the last 15 years were collected and classified in 3 clusters: (i) conceptual contribution, (ii) technological development and (iii) industrial applications. The most common reasons for modelling were: (i) providing insights for product / process design, (ii) optimizing operations, and (iii) supporting financial and feasibility assessment. Generally, LCC, LCE and LCA methodologies were applied together in these research works, supported by a simulation tool for testing and estimating different application scenarios [3]. In summary, simulation is generally used for the evaluation of two main issues: (i) product life cycle-related costs and (ii) product life cycle-related environmental impacts. In both these categories, a wide range of simulation tools were developed, from spread-sheets, mathematical software, and programming languages to specialist computational packages. However there are several discordances in the definition of lifecycle boundaries and which should be the inputs and outputs of the simulation.

The interesting point, which comes out from this research, is the completely discordance between the different authors and the lack of a well-defined approach in the lifecycle simulation area.

3. Framework

In the previous section the state of the art about the lifecycle perspective is described. As previously described, a huge quantity of literature was written on this topic, in particular for Life Cycle Costing and Life Cycle Assessment methodologies.

Nowadays they are consolidated methodologies (studied by 60ies); however they were rarely applied together. Moreover, the two methodologies don't allow the exploration of all the possible alternatives, in order to find the best life cycle oriented solution.

In the light of these deficiencies, the aim is to build an integrated, structured and robust model, completed by methods / techniques, to support and help the activity of designers and system engineers, in order to create and identify the optimal lifecycle oriented solution. Fig. 1 described the conceptual framework of the proposed model.

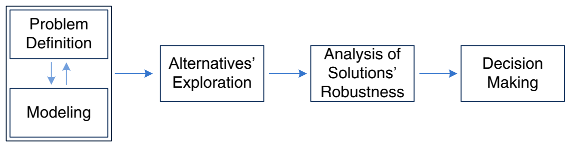

Fig. 1. Conceptual Framework

Conceptual Framework is composed by 4 main blocks: Problem Definition and Modeling, Alternatives' Exploration, Analysis of Solutions' Robustness and Decision Making. Moreover, it is the representation of the different steps of the model proposed. The blocks are described below:

Problem Definition and Modeling: first block is dedicated to the definition and modeling of the problem, focusing on lifecycle perspectives. In detail, Modeling component will be built on the existing integrated methodologies, which consider both economic and environmental dimensions, and on the existing Life Cycle X methodologies. The block will study which are the necessary data and information, and how to collect them, considering: (i) life cycle costs, (ii) life cycle environmental impacts, (iii) technical constraints and / or performances. Moreover, the problem will be defined, considering the customers' needs and constraints. The output of this block will be all the possible alternatives for realizing the manufacturing system and all the necessary information and data to perform the next blocks. Finally, the two components of this block, Problem Definition and Modeling, are mutually correlated: Problem Definition influences the creation of the model; Modeling (related to the Life Cycle Methodologies) influences the data gathering.

Alternatives' Exploration: second block will analyze techniques / methods for narrowing the number of solutions, observing life cycle costs and environmental impacts. As previously shown in state of the art section, optimization and simulation methods will be analyzed and depth. Moreover, other methods and techniques will be evaluated. The objective will be to find which methods / techniques can be used, in order to explore and narrow the number of possible alternatives (Output of previous block), selecting a set of optimal ones.

Analysis of Solutions' Robustness: third block will analyze techniques / methods for evaluating the solutions' robustness. The objective will be to find which methods / techniques can be used for analyzing robustness of the solutions. In particular, life cycle simulation methods deserve a particular attention. Indeed, simulation methods are borderline, due to they can explore and narrow the possible alternatives, but they can also permit a robustness analysis. Analyzing the set of optimal solutions (Output of previous block), this block will return a narrow set of optimal and robustness solutions.

Decision making: fourth block will analyze techniques / methods for choosing the more appropriate life cycle oriented solution, starting from the Output of previous block.

4. Firsts Results

In this section first results, obtained by the application of the proposed model, will be presented. In particular, first two blocks of the conceptual framework, which are Problem Definition and Modeling and Alternatives' Exploration, were performed.

Industrial case is provided by a global supplier of industrial automation systems and services, mainly for the automotive manufacturing sector. It provides the entire systems (composed by machining centers, assembly stations and / or robots). The company interest in lifecycle optimization arises from their real needs. Indeed more and more customers are measuring their suppliers in terms of "product life cycle" performances. They choose the solution with lower life cycle costs and less polluting impacts. For getting the order, the supplier company might evaluate and declare these life cycle performances since the first Request for Quotation.

The provided industrial case regards a fraction of assembly line for a small car diesel engine.

The different stations, for a total of 5, can have several alternatives, 6 for each station. Alternatives can be automatic (aut), semi-automatic (saut) or manual (m) stations. Therefore there are 6^5 possible lines. The problem is a multi-objective one, with two objectives: (i) minimization of the life cycle costs and (ii) minimization of the life cycle impacts of the line. Moreover, availability of the line must be greater than a threshold value. Therefore, the objective is to find the best life cycle oriented solution, in terms of costs and environmental impacts, respecting a technical constraint.

Data are gathered from company database, where the majority of them are estimations. To evaluate the environmental impacts, Eco-Indicator 99 is used as S-LCA (Simplified Life Cycle Assessment) approach. However, only environmental impact of the station, in terms of materials used, and of the power consumption are calculated, due to lack of information. The access of different voices of cost, instead, is easy. This description is about Problem Definition and Modeling block.

In the next lines, Alternatives' Exploration block will be described. Analyzing the type of problem and the number of possible alternatives, multi-objective optimization method has been chosen to narrow the number of alternatives, obtaining a set of optimal solutions. Genetic algorithm is applied for the following reasons: (i) it is more efficient than others when number of variables increase; (ii) it doesn't have any problem with multi-objective optimization; (iii) it is suitable for applications dealing with component-based systems (the line could be seen as a chromosome and the stations as genes). In literature different multi-objective genetic algorithms exist, however NSGA-2 [5] is chosen because it is one of the most popular and tested Genetic Algorithms. Referring to Problem Definition and Modeling block, a model based on NSGA-2 is built. As previously described, it has two objectives (minimization of costs and environmental impacts along the product life cycle) and one constraint (availability of the line must be greater than a threshold value). To perform NSGA-2 it is used GANetXL [23], an add-in for Microsoft Excel.

The results are reported below in the graph (Fig. 2).

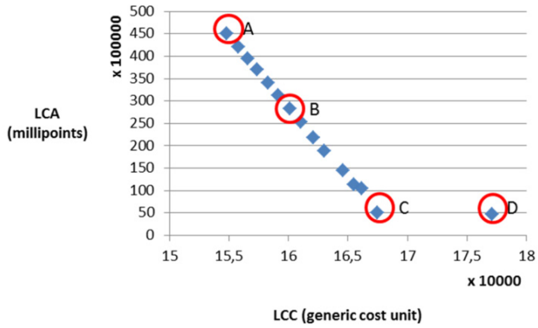

Fig. 2. Graph of the results

All the solutions are optimal, because they are non-dominated ones, distributed along the Pareto curve. The set of optimal solutions had a dimension of 59 solutions. Here in the graph only the most representative 15solutions are reported.

Each point carries a series of information, reported in the table: (i) the product lifecycle costs, (ii) the product lifecycle environmental impacts and (iii) the stations that build the line.

Four values of the graph are selected to show it (Table 1).

Table 1. Results

	Min LCC (generic unit cost)	Min LCA (millipoints)	Stations
A	154823	45048190	2(aut)7(aut)13(aut) 20(aut) 26(aut)
B	160104.7	28230730	2(aut)9(aut) 18(m) 20(aut) 30(m)
C	167493.8	5062750	6(m) 12(m) 18(m) 24(m) 30(m)
D	177139.6	4627975	6(m) 12(m) 18(m) 23(saut) 30(m)

Results of this first analysis are validated by designers and engineers of the company.

Clearly, other blocks of the proposed model (Analysis of Solutions' Robustness and Decision Making) are necessary to conduct designers and engineers at reaching of the best lifecycle oriented solution.

5. Conclusion

In this paper, an integrated, structured and robust model, completed by methods / techniques, to support and help the activity of designers and engineers to create and identify optimal life cycle oriented solution is presented. Introduction (Section 1) points out the factors and the context where European companies operate, underscoring the importance to be eco-efficient and to realize green products / systems, keeping a low cost of ownership for their customers. In particular, European companies must be able to realize the best life cycle oriented solution. Analyzing the state of the art about life cycle methodology (Section 2), two methodologies for evaluating costs and environmental impacts are developed: Life Cycle Costing (LCC) and Life Cycle Assessment (LCA).

However, these methodologies are not sufficient to explore different alternatives, in order to find the best solution. Therefore, it is necessary to apply methods and techniques so as to explore the different alternatives, evaluating costs, environmental impacts and technical performances along the product / system lifecycle.

In literature these methods can be grouped into 2 main areas: optimization and simulation.

To reach the aim of the paper, in Section 3 a first conceptual framework of the model is proposed (more detail are within the section).

In section 4 the proposed model is partially applied (only Problem Definition and Modeling and Alternatives' Exploration blocks) on a real industrial case, showing the firs results. As highlighted in section 4, the proposed model is able to narrow the possible alternatives from 6^5 to 59 optimal solutions. Therefore, it is clear that this model can generate benefits during its application. Designers and system engineers have appreciated this model, because it allows to explore quickly different alternatives, returning the optimal ones.

However future developments are necessary to improve the proposed model.

First of all, literature will be explored better and in depth, in order to: (i) define all the existing methods / techniques, (ii) classify them and (iii) select the more appropriate for the model. Main efforts will be directed in the development of Analysis of Solutions' Robustness and Decision Making blocks.

Secondly, a new industrial case will be searched, to test in depth the proposed model, in order to generalize the model.

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