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Towards a design-to-sustainability platform based on functional representations and simplified geometric layouts

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ABSTRACT
Sustainability is becoming one of the main drivers of the modern product and system design. However, sustainability assessments are usually carried out at the end of the design process to check the validity of the decisions already taken. As a consequence, when targets are not achieved, numerous time-consuming iteration loops are necessary to optimize the initial solution. The paper merges functional-based and design-to-cost approaches to propose a CAD-based platform able to assess product lifecycle costs and impacts from the earliest design stages by configuring and assessing feasible design solutions. It considers both economic expenses and environmental impacts during all phases of product lifecycle on the basis of the company knowledge.

KEYWORDS
Design-to-cost; functional design; CAD; lifecycle approach; sustainability

1. Introduction

The actual industrial scenario is characterized by a strong competitiveness extended to global markets and, at the same time, a growing attention to resource consumption and optimization. In this context, design optimization in respect with product performance is one of the biggest challenges for modern manufacturing industry, independently from the specific industrial sector or country. However, traditionally cost and environmental issues are rarely considered as design drivers from the earliest design stages, but they are rather a design output; as a consequence, preliminary design is usually developed without considering such issues and numerous process iterations occur when project targets are not respected. The main reason of late analyses is due to the lack of sustainability-oriented design strategies and effective supporting tools for estimating cost and environmental impacts from the conceptual design.

Although sustainability analysis is a very strategic activity in product design for the majority of companies, inefficient methods and tools are actually available to support such crucial task. Product cost is usually estimated at the beginning of the design process by qualitative methods based on the subjective experience and intuition of few expert people [8], and is concretely defined and deeply analysed only at the end of the design process, when the project is almost conceived, by quantitative estimating techniques [18]. Such techniques exploit mathematical algorithms and statistical tools and are highly time-consuming since they require a synthetic analysis of manufacturing knowledge and a successful collaboration among the numerous actors involved in cost and performance evaluation. However, in late design stages, there are limited possibilities of effective design change and only minor corrective actions can be taken, generating a long iteration loop that risks to be time wasting and unsatisfactory. Several studies demonstrated that a large percentage (at least 70% up to 80%) of product cost is already determined during the conceptual phase and, when at end of the detailed design (when it goes into production), 95% of its cost is already committed [7]. As a consequence, most of the costs are already frozen with product conceptualization and the cost of engineering changes is growing exponentially through the stages of the development process [1, 24].

During the last decades, some methodologies and theoretical approaches have been defined to accurately assess cost before product realization and optimize the design anticipating manufacturing criticalities. One of the founding theories is probability Design for Manufacturing and Assembly (DFMA), which considers manufacturing effort and cost related to fabrication and assembly processes in order to simplify production and assembly and to finally reduce the related time and cost [3]. Subsequently, other methodologies were defined to manage the knowledge connected to cost definition (e.g. Group Technology, Feature-based analysis, Computer-Aided Process Planning (CAPP)). Among them, Design

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to Cost (DTC) proposed to define a target cost to be respected and fall back costs to early design stage so that the conceptual phase continually interacts with cost considerations [11].

Recently, some software tools based on such theories are available on the market to support designers and managers. Among them, Feature-Based Costing (FBC) tools use product features to describe product geometric information at different levels of detail [30], and they can be used to collect all functional and technological information (tolerances, surface finishing, manufacturing cycle, etc.) [23]. Parametric feature-based 3D CAD systems can represent the practical support to manage cost information along with the functional product definition and its virtual representation from the early design stages. Recently, few interesting feature-based costing technology has been developed and deployed as knowledge-based systems [5, 27]. However, they are usually very complex to use and require a deep knowledge and a technological background, so they are not suited for designers but rather for cost engineers. Moreover, cost estimation is usually limited to the manufacturing phase and does not consider the whole product lifecycle, including also use and end-of-life stages. For these reasons, their application in industry is rare due to hard implementation, numerous resources to be involved, and high effort in knowledge management and data analysis.

According to these evidences, the present paper proposes a functional-based design platform to support an effective design-to-sustainability approach according to a lifecycle perspective. It adopts a functional-based approach to identify the functional features of a product, starting for the analysis of a preliminary geometry of the design concept and estimating the product cost and environmental impact along its lifecycle. Then, it proposes the best design configuration according to the project requirements on the basis of the company knowledge. Such a tool can be used from the early design stages to identify the best design features and production processes according to the project target cost, available technologies and quantities to be produced. Global sustainability of the designed product is finally expressed in terms of cost expenses on the whole lifecycle: they consider both economic and environmental impacts, normalized in term of costs, during all product lifecycle phases, from raw material supply to manufacturing, assembling, logistics, as well as consumption during its lifetime, until disassembly, dismantling and disposal.

The paper discuss the need and the goals of such a platform, describes the designed solution and the parts it is composed of, and finally, outlines the applicability in an industrial context.

2. Context and related works

2.1. Functional approach for design-to-cost

In order to perform early "Design to Cost" (DTC) evaluations, design alternatives and solutions need to be rapidly figured out and assessed. During new product definition, designers work at an abstract level mostly in terms of functional concepts [21]. In the research community the function is agreed as a means of describing a product with abstract blocks, without having to consider physical principles, material selection, and geometric shapes, as in Pahl et al. [21]. However, it has been noticed that there is a little consensus on what a "function" is and very often it is confused with the concept of "behaviour" [28]. The first is limited to an abstract action, which is accomplished in a product, while the second includes the way it is implemented by applying physical principles. Despite attention given by Academia, designers not explicitly use functional concepts in their daily activities and no computer tools have been developed for giving them an effective support [9]. Therefore, it is mandatory to support the representation of functional, or at least behavioral, structure of the product. As appointed by Van der Vegte et al. [29], some open issues still emerge in employing the functional modeling in industry. They refer to four main points: (a) mapping requirements onto functions, (b) matching targeted functions to first principles and physical processes, (c) mapping functional arrangements to structural arrangements and (d) coping with the abstraction, incompleteness, and uncertainties in conceptual modeling.

Design expertise related to the embodiment of the functions in technical solutions is another important issue to be considered in DTC approach. It regards the set of explicit and implicit design procedures, technics, knowledge, and best practices. In its daily activity, the design team chooses a set of design solutions, by both optimization of existing products or engineering new ones, from complex and iterative processes where reached solutions are hopefully optimized against few criteria. The role of a knowledge management system to support design activities is emerging. The designer is nowadays exposed to a considerable amount of data and information coming from the company background and the external sources. The former refers to past solutions, dimensioning rules, internal regulations, production and maintenance reports, comments from the customers, etc., which are available in the company documents, above all in the form of CAD models, or ERP and PLM records. The latter refers to Internet data and external services provided by suppliers, which represent an additional and valuable source of knowledge. However, such data are often accessible in a poor structured manner.

In the meanwhile, development times are becoming shorter and shorter due to strong competitiveness limiting the possibility of deeper evaluations. This leads to miss chances of defining truly optimized solutions, especially from cost and environmental side. In fact, functional and production issues are necessarily considered a priority, while other aspects are neglected due to time shortages. Indeed, current methods for cost and environmental assessment require a certain level of detail of the solution in order to figure the required technologies and resources relative to the production, use and end of life phases. Therefore, cost optimization can be reached from efficient recovery, representation and transfer of knowledge relative to systems design. In this context, Chandrasegaran et al. [4] widely reviewed the existing approaches for knowledge representation and highlighted some trends for future that confirm the observations made above, in particular: the need of intelligent systems to act as problem solvers; the chance of introducing knowledge-based design systems and computational frameworks to support sustainability evaluations; the necessity of ontologies to encode the design rationale. Regarding the last point, it is important to recall the MEml initiative (i.e. Mechanical Engineering modeling language), which is a tentative of capturing, representing and modeling the mechanical engineering knowledge reconciling previous efforts in functional, behavioral and structural representations [28].

2.2. Lifecycle cost estimation

Life Cycle Cost Analysis (LCCA) is a methodology for the quantification and analysis of the costs incurred in the product lifecycle (LCC). Firstly defined and used by the US Department of Defence in the mid-1960s, twenty years later it was adapted for the building investment evaluation. During the last decade, several handbooks describing the LCCA have been issued with the aim to support companies in widening their vision to the whole Life Cycle of a product [6]. The complexity of LCCA is strictly related to the prediction of future costs related to manufacturing, use and disposal of a product or a machine in general. Moreover, LCCA is used as a method to compare alternative design solutions, suppliers and use profile, so that its application is required yet during the early design phase (if developing a new product or machine) or during the early asset investment analysis (if purchasing a new asset).

Several researchers, even if targeted to specific sectors, tried to apply the LCCA during the early design stage. An interesting research approach was defined to model the building in such a way that LCC can already be calculated in the early design phases, even when no design for the building is yet available at the definition of requirements [15]. Peng et al. [22] addressed the same problem in the marine sector; they presented a systematic analysis on the bottom attributes' measurement indexes of the navy vessel LCC's components, and provided the measurement indexes that can reflect LCC's characteristics. Seo et al. [26] defined a general method for providing a preliminary LCC, which is approximated but quickly to define, by using Artificial Neural Networks (ANNs) to generalise product attributes and life cycle cost data from pre-existing LCC studies. Kovacic et al. [17] presented a comparative study of three commercial software-tools for LCC-calculation, and tested how they fitted for the implementation in the early building design. The analysis showed that any tool could be employed without adoption and customization, lacking of benchmarks and extensive data.

The LCCA is also widely used for asset management of manufacturing plant. In this sector, the Total Cost of Ownership Analysis (TCOA) is used in place of LCCA. Indeed, LCC is defined as the Total Cost of Ownership (TCO) of a machinery or equipment, including costs of acquisition, operation, maintenance, and conversion / decommission [2]. In general, the TCO of an asset is determined summing all the costs directly attributable to owning or using the asset itself. As for the LCCA, also literature related to TCOA is rich of guidelines and procedures to account and discount the cost items in a proper way [20]. For instance, Ellram [10] proposed a way for classifying the TCOA methods and examined how firms can use TCOA to identify barriers and benefits in purchasing.

However, "traditional" LCCA methods and tools don't usually consider also the environmental aspects, even though they contain the words "lifecycle". Several studies are addressing this challenge, trying to combine economic and environmental aspects along the whole life cycle. Norris [19] demonstrated how full-scale, standard methods of LCA can and have been tightly, logically and practically integrated with standard methods for cost accounting and life cycle cost analysis. Kjær et al. [16] investigated how LCC and LCA can be integrated by using the same financial and inventory data. The method used to translate LCC into an LCA is based on environmental input-output LCA. Senthil et al. [25] developed a Life Cycle Environmental Cost Analysis (LCECA) model to incorporate costing into the LCA practice. The mathematical model of LCECA determines quantitative expressions between the total cost of products and the various eco-costs. Gluch and Baumann [14] recorder ten LCC-oriented environmental accounting tools suggested as useful in environmental decision-making. However, their implementation seems to be limited, which opens up for a conceptual discussion, so that the authors discuss about the practical usefulness of the LCC approach in making environmentally responsible investment decisions.

According to the state of the art, it is possible to conclude that literature lacks of tools for a comprehensive LCCA that can be used by designers from the initial design stages for an effective cost and environmental assessment at the same time, providing a simple and consolidate impact early evaluation. Moreover, LCCA solutions should be shared along the product development process, from the conceptual design until to the detailed design, and scalable cost models are required in order to be used with an increasing level of detail while the product model evolves during its development. AT the same time, LCCA tools should be used, as the same time, for LCC estimation during the early design stage and investment analysis for the investment evaluation of new assets.

3. The research approach

3.1. Research goals

The research focuses on the definition of a functional-based design platform to support an effective design-to-sustainability approach according to a lifecycle perspective. Such a platform can be used from the early design stages to identify the best design features and the most suitable production processes according to the project target cost, available technologies and quantities to be produced. The final cost value expresses the whole lifecycle sustainability impact of the designed product: it considers both economic expenses and environmental impacts, normalized in term of cost impact, and all phases of product lifecycle, from raw material to manufacturing stages, assembling, logistics, consumption during its lifetime, until disassembly, dismantling and disposal.

Such a tool will support designers in everyday product design and evolve the traditional design process, as shown in Fig. 1. In fact, designers traditionally conceive both geometries and product structure on the basis of their experience and knowledge and develop the detailed project. When the project is almost completed, they collaborate with cost engineers, analysts and technologists to define the production cycle and to determine product cost and environmental impacts. Whether targets are not achieved, designers are called to modify the initial project to better match with manufacturing and assembly requirements by changing materials, geometries and/or product structure to fix cost and environmental issues (Fig. 1-A). With the adoption of the proposed design-to-sustainability platform, designers can exploit the company knowledge about manufacturing, use and End-of-Life (EoL) processes, properly formalized in databases, to adopt a set of cost and impact models to the preliminary design solutions in order to have an early estimation of cost and impacts for each of the conceived solutions.

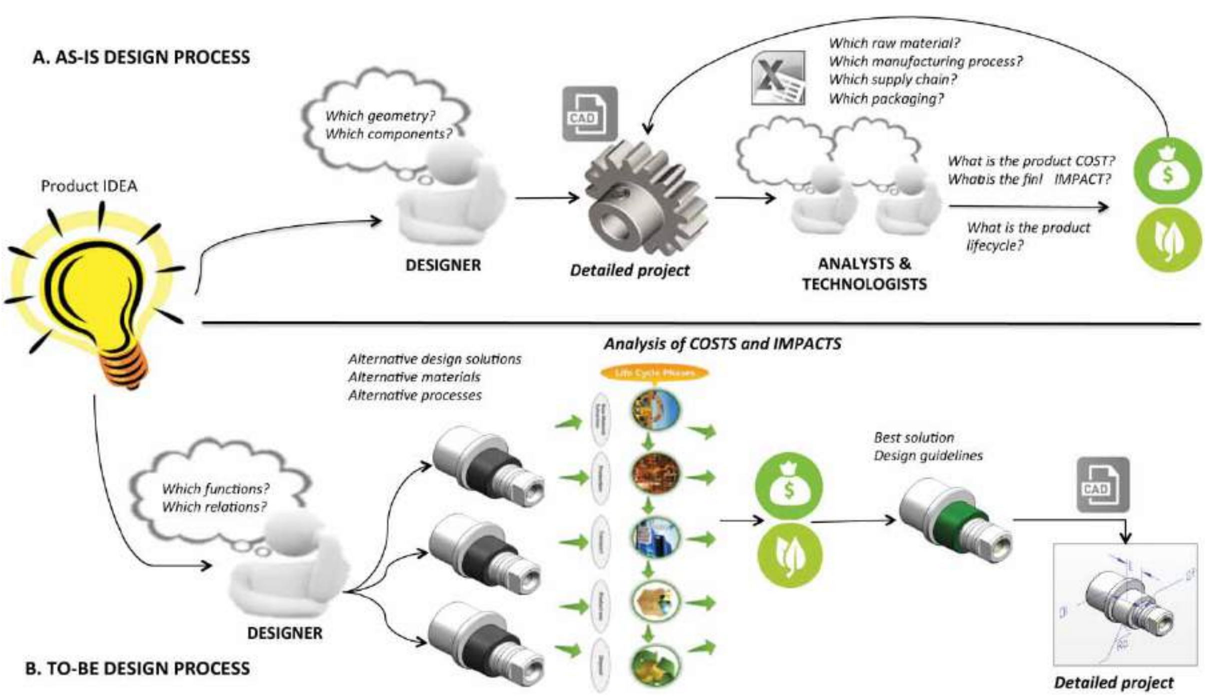

Figure 1. Comparison between AS-IS (A at the top) and TO-BE (B at the bottom) design process.

In this way, cost and environmental targets directly drive the design choices and the best solution satisfying the project requirements can be easily and quickly defined. After that, the detailed project is developed and early assessment verified and validated (Fig. 1-B).

In comparison with the existing tools and approaches, the research aims at extending the actual scenario of CAD-based solutions for cost or impact assessment. In fact, actual cost estimating approaches can be used mainly in the detailed design stage, refer to product without caring about processes, and focus on manufacturing phases. Fig. 2 highlights the area covered by the actual methodologies with a green box. The proposed approach wants to extend all three axes of the considered domain by the following objectives:

- Anticipating the estimation on the conceptual stages, as far as product design phases are concerned;
- Including also processes together with products, about the application context;
- Extending the analysis to all the lifecycle phases according to "from cradle to grave" philosophy, instead of limiting the analysis to manufacturing.

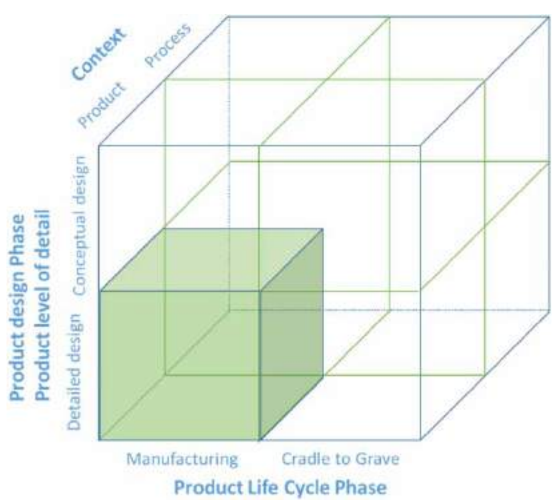

Figure 2. The extended workspace of the proposed design-to-sustainability platform (green box indicates the area covered by actual tools).

3.2. The design-to-sustainability approach

The research aims to define a specific design-to-sustainability approach that combines design-to-cost and lifecycle costing methodologies. The former allows managing design configurations by identifying the product functional features, and defining the best design according to the design constraints in terms of costs and performances to be achieved, while the latter assesses costs and impacts of products and processes according to specific cost and impact models covering all the product lifecycle phases. Knowledge-based approaches are adopted to properly structure the design knowledge and define the models to calculate costs and impacts. Furthermore, search and configuration algorithms will be developed to suggest design solutions in an intelligent way according to the technical specifications, product performances and cost/impact targets.

The proposed approach targets the assessment of product sustainability at an early design stage on the basis of preliminary product configuration obtained combining company knowledge and past solutions. In this way, a set of configurations able to satisfy the sustainability requirements is suggested to the designer, and the global impact of costs and environment for each of them is proposed. This approach allows designers to easily evaluate the cost and the impacts of the designed product, compare alternatives, have suggestions about cost-effective solutions, and monitor the cost and the environmental impact evolution during the project. Such an approach can be integrated into a software platform to effectively support designers' work and also exploit data and information directly retrieved from 3D CAD models, saving time and effort spent.

The main contributions of the paper can be summarized as follows:

- formalization of the entire product lifecycle and design rationale, from the voice of the customer to the End of Life scenario;
- combination of functional structure concepts with simplified geometrical layouts to drive the choice of the more efficient and sustainable product parts, configuration and arrangements;
- definition and management of product geometries at different levels of detail as the design process advances.

3.3. The solution configuration

The first goal of the proposed approach is to support the definition of sustainable configurations of the solution. For this purpose, designer has to be firstly supported in the rapid definition of several valid design solutions according to the specific project requirements, called Preliminary Design Solutions (PDSs). A PDS is a triple formed by a Functional / Behavioral Structure (FS), an implementation Structure with dimensioning Parameters (SP) and a Geometrical Elementary Representation (GER) as in Fig. 3. The PDS database is progressively increased by the everyday activity of designer department. New PDSs and the ones coming from previously

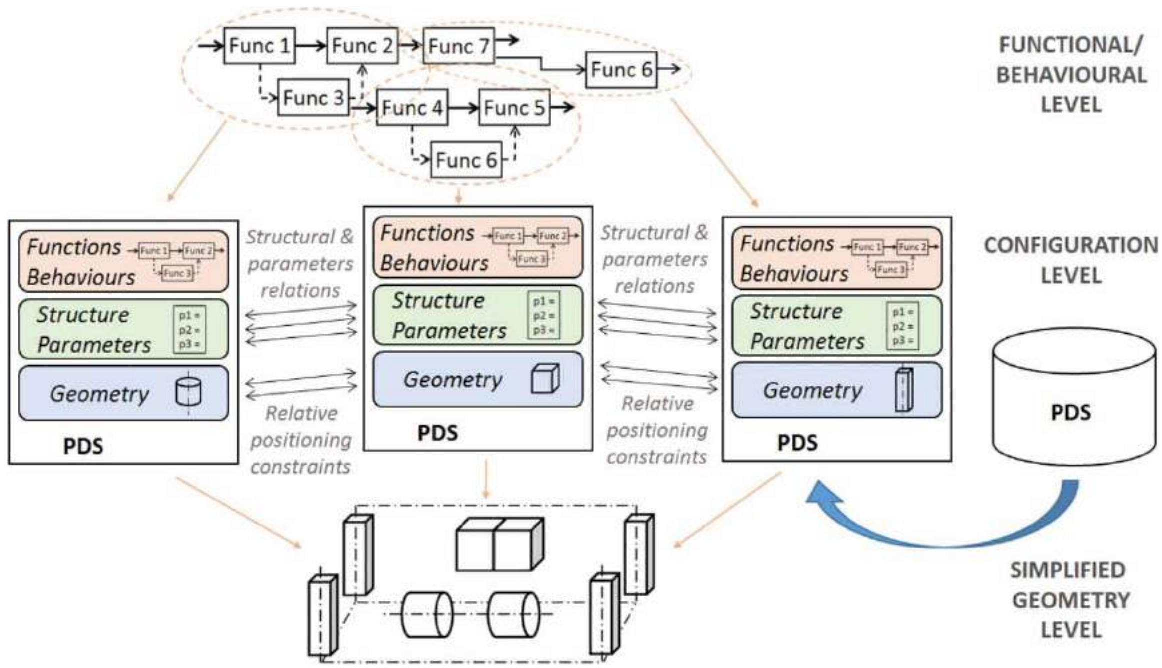

Figure 3. Structure of PDSs and connections between parameters and spatial positions.

implemented solutions are progressively added to widen the managed knowledge.

The main characteristics of such PDSs are:

- *validity*, i.e. correct functional and embodiment structures which guarantee the expected product requirements and performances;
- *completeness*, i.e. it must guarantee the definition of all the product modules and the relative parameters which act as drivers for the cost and environmental impacts computation;
- *simplicity*, i.e. parameterization must be as slender and intuitive as possible in order to be easily communicated, while useless design details that can be defined in subsequent embodiment phases must be neglected;
- *agility*, i.e. the capability of being easily modified and rearranged by the designer;
- *modularity*, i.e. the product is given by the combination of self-contained units (modules) with limited and standardized interfaces;
- *granularity*, i.e. the capability of being arranged in an hierarchical manner in order to progressively form sub-groups, groups, products, production lines, plants.

The FS refers to the graph of sub-functions connected by flows of material, energy and signal. Along with pure functional definitions, behaviors are included in the FS definitions and flows are characterized with magnitude values. FS structures come from the given product requirements and are defined thanks to a graphical environment: starting from the list of requirements, the designer is able to determine a required functional structure and the flows among sub-functions. Groups of sub-functions are then recognizable in a Database of PDSs, which store in this form the company know-how and the past solutions. Possible implementations are then recovered from the PDS sharing the same FS. The set of available PDS allows the arrangement and configuration of several preliminary layouts of the product. Finally, the GERs refer to simplified geometric representations made of simple shapes (axis, boxes, cylinders, etc.) and textual or symbolic annotations to clarify given meanings and additional information. A GER aims to represent in the simplest forms the embodiment given to a certain FS, by means of more sophisticated components with simple shapes by fixing the relevant data required at a preliminary stage: parameters to express overall dimensions, distances and mating constraints to locate the parts, annotations to provide technical details to the shapes, marks to geometrical entities which represent interfaces to other PDSs. The geometrical arrangement is given imposing spatial constraints among the GERs. GERs are built of entities that represent the final detailed implementation of the PDS (i.e. relevant axes or reference planes, flanges, interfaces, sides of the overall size (bounding box)). Such entities form invariant geometries, which are recognizable in the geometry assumed by the parts as following design activities are performed allowing a continuous updating of the geometrical arrangement until the final product design. The aim of the geometrical arrangement is to provide a preliminary design of the solution in order to make feasibility evaluations and provide additional data for the subsequent LCC analysis.

3.4. The early estimation of the lifecycle impact

Once a preliminary arrangement of the product is obtained, an early Life Cycle Costing (LCC) assessment of the configured products is carried out. For this purpose, the solution configuration approach is coupled with a lifecycle impact estimation approach based on parametric cost models of manufacturing, use and EoL phases. Such cost models are originated from the detailed analysis of existing design solutions. They are then parameterized on the basis of the most relevant design parameters for families of homogeneous solutions. For a pinion-shaft product family, for instance, the most relevant design parameters for a parametric calculation of the life cycle cost are: material, shaft length, shaft diameter, pinion parameters such as number of teeth, module and type (straight-cut, helical, double helical). In case of an electric motor, design parameters are: type (brushless, asynchronous, etc.), electric maximum power, rotational speed, maximum torque, number of working points, overall dimensions and cooling system. In general, the number of the chosen parameters depends of the level of accuracy required by the specific application context. Manufacturing cost models are based on Cicconi et al. [5].

The use phase cost models mainly include energy consumption and maintenance cost, which mostly determine the running costs. Energy consumption is given by the sum of the energy required by the components in the system, i.e. by multiplying the working time and requested power, and by considering an efficiency curve, which depends on the application and the energy source. Cost models for maintenance operations are obtained in a similar way. EoL phase cost models mainly consider costs for disassembly and dismantling processes, where disassembly costs are estimated from disassembly time, analytically calculated considering the list of disassembly operations and time required for each of them to remove a specific component according to the connection type (i.e. magnetic, mechanical, electrical, etc.) and the component characteristics (i.e. weight, level of wear and corrosion, etc.) [13]. Moreover, according to the selected EoL scenario (e.g. removal of target components for maintenance, remanufacturing or recycling, etc.), cost models of single operations are combined in order to create a dismantling process (e.g. manual disassembly, shredding, cleaning, etc.).

The parametric cost models are therefore realized by pre-defined configurations of the detailed cost models, built according to the type of component and the manufacturing, use and EoL scenarios (e.g. manual dismantling for maintenance or remanufacturing, shredding for recycling, etc.). Each configuration is characterized by general parameters, which are usually known during the conceptual design stage and drive the detailed cost models without any additional input by the user.

Finally, the same information used for the cost models is also used for a simplified environmental Life Cycle Assessment (S-LCA), mainly for a comparative evaluation among more feasible design solutions. For instance, energy consumption is considered also for environmental impact assessment since it mainly characterizes the use and manufacturing phases. The electricity mix, depending on the specific country, is used to calculate the carbon footprint, one of the most important environmental indicators. In this way, all the parameters available in the cost models (i.e. electric power, cutting tool consumption, etc.) allow further environmental indicators (i.e. CO2 emission) to be calculated for a more comprehensive analysis.

The proposed approach extends also to processes and production lines in order to estimate the Total Cost of Ownership (TCO) and to support the investment analysis. Indeed, the configuration approach can be used for products as well as for manufacturing process configuration: in this case, the production line, made by a sets of machines, is configured according to the product to be processed. For each machine, a TCO value is calculated by summing the initial costs (i.e. price and start-up cost) and the running costs (i.e. energy and maintenance) as indicated in [12].

4. The design-to-sustainability platform

4.1. The platform architecture

The design-to-sustainability system platform has been defined analysing the literature and several industrial design processes. After some refining work the structure presented in this section has been finally conceived. It is structured by five modules; each of them addresses a specific topic of the proposed approach, and cooperates with the others by exchanging information and input-output data into unique software architecture.

Fig. 4 shows system modules and databases, and the main interconnections among modules and data flows. The modules are:

- *Geometrical Analyzer* (GA): it allows the geometrical parameters to be automatically extracted from

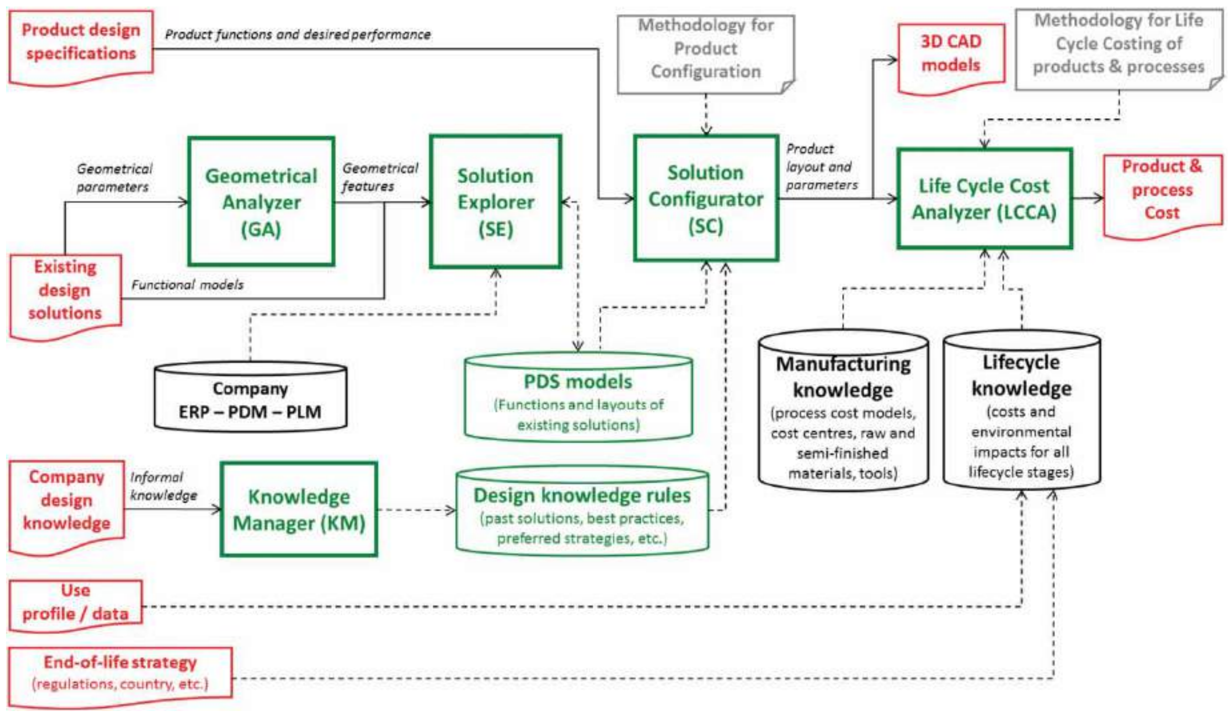

Figure 4. Design-to-sustainability platform architecture.

the 3D CAD model of the actual preliminary design solution in order to be translated into relevant geometrical features;

- *Knowledge Manager* (KM): it recovers and classifies the company informal knowledge into a set of qualitative and quantitative design rules expressing the company best practices and preferred strategies;
- *Solution Explorer* (SE): it catalogues existing solutions from company historical data and groups them according to homogeneity and functional similarity with the actual solution according to search algorithms on company databases (i.e. ERP, PDM, PLM) and analysis of geometrical features from 3D CAD models.
- *Solution Configurator* (SC): it allows the new product to be described by functions and its functional model to be defined according to the company design knowledge to finally define design guidelines and configure the detailed 3D CAD models;
- *Life Cycle Cost Analyzer* (LCCA): it assesses the economical impact of the configured solutions considering the whole lifecycle (from manufacturing to use, management, and end-of-life) and both direct and indirect costs (i.e. administration, training, technical support, fixed cost). The calculated impacts refer to economical cost and cost due to environmental pollution.

The main purpose is to support the designer to define the best design solution according to a set of design drivers. The main design optimization drivers have been identified in:

- minimizing the number of parts,
- simplifying the shapes,
- optimizing dimensions and weight,
- reducing process time and cost by optimizing the technological parameters,
- reducing the types of materials adopted,
- standardizing the parts and reusing components,
- optimizing investment.

4.2. Early assessment of costs and environmental impacts

The proposed approach is under experimentation in collaboration with the design and engineering departments of few partner companies, belonging to different industrial sector in order to test the proposed approach on different case studies and optimize the system platform to be used in different contexts of application. In particular, products such as gearboxes, operating machines, cranes, gas turbine ducts, and food processing lines have been studied so far and their lifecycle deeply analysed. The preliminary platform has moved from the functional and modular analysis of the selected products, where simplified geometrical layouts have been drawn and parameterized. Then, new products have been configured following the proposed approach in order to test the approach feasibility and the validity of the new solutions.

In order to illustrate how the proposed platform works, an application example is reported. It concerns the application to a baseplate module of a power train, hosting gearboxes, compressors for oil or gas pumping, turbines and motors (Fig. 5). The typical arrangement of this kind of plants comprehends trains of compressors, which are powered by gas turbines and optional auxiliary motor (Fig. 5-A). The machines are located on baseplates, which are designed for inshore or offshore applications, and design variants are due to the sizes of the powering gas turbines, the sizes and shape of the compressors, geometrical constraints on the shape of the baseplate given by the installation deck (Fig. 5-B). Starting from the left of the figure, the system is composed by the housing, which host the gas turbine, the gearbox to reduce the rotational speed, and the power generator. The lubrication oil control unit is shown in the front.

A new solution is defined starting from a new functional layout that emerges from customer requirements. Design input data includes the size and performances of the main modules (i.e. turbine and compressors, the available space on the installation platform, additional geometrical constraints such as obstacles and imposed positions) and, finally, expected performances in terms of noise, consumption and environmental impacts. Fig. 6 shows an example of a compressor PDS model, where the product geometry is detailed from catalogue parameters and mating constraints and distances to other PDSs are defined. Fig. 7 shows the arrangement of the steelwork baseplate, where the baseplate is defined from a simplified layout made of a network of lines representing the axes of the beams and geometries of the machines.

In particular, the LCCA has been carried out during the preliminary design stage for the compressor, starting from the results of the modular analysis: the product has been broke down in modules (rotor, stator, motor, controller, etc.). Each module has been subsequently characterized by attributes, which mainly define the overall geometry (i.e. dimensions, weight, material, class tolerance) and performance (i.e. power, efficiency, rotational speed, flow rate). The manufacturing cost is given by the sum of costs for materials, engineering stages, manufacturing processes, and installation. Material cost is calculated by analysing historical data of the same product family. The total amount is split for each category of material (i.e. stainless steel, carbon steel, super alloy, etc.). The cost of each material category is discounted from the last quotation available according to the material cost trend defined by the stock exchange. The overall unitary material cost is then multiplied by the product weight.

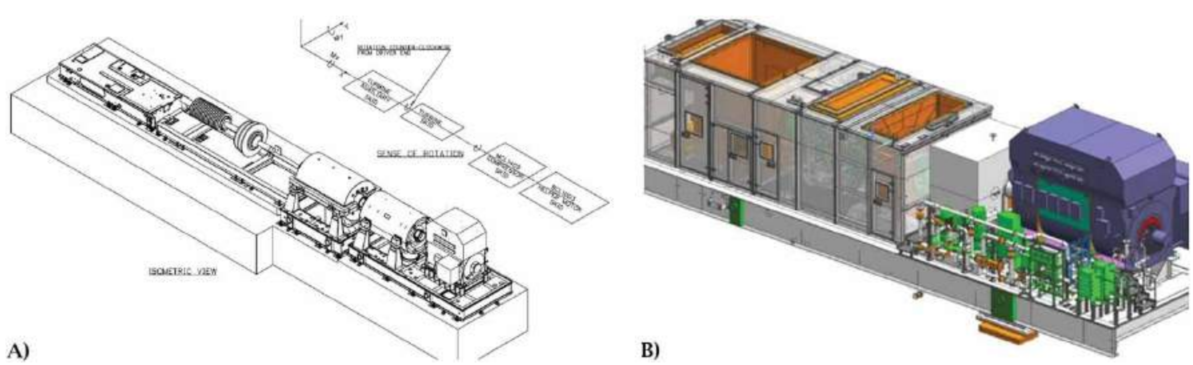

Figure 5. Schematic arrangement of a power train (A) and example of configuration of an offshore turbo-generator (B).

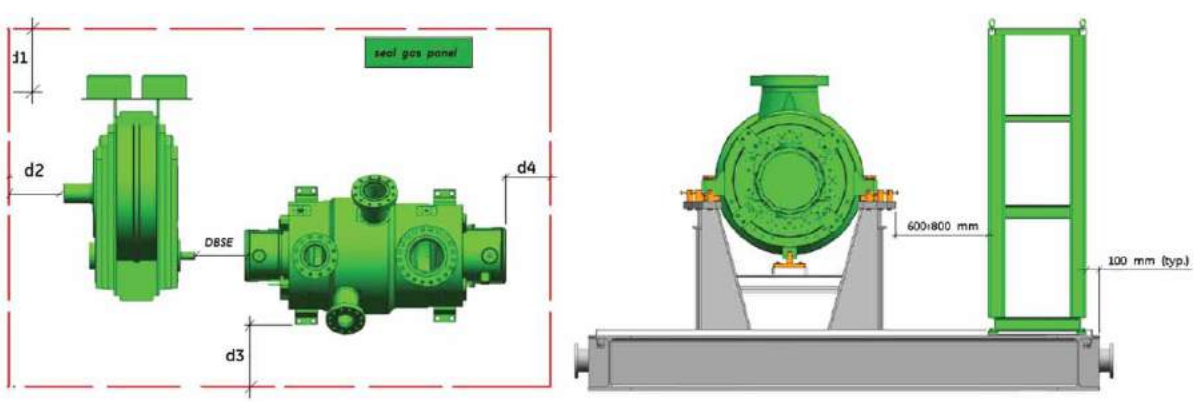

Figure 6. Example of a compressor PSD model.

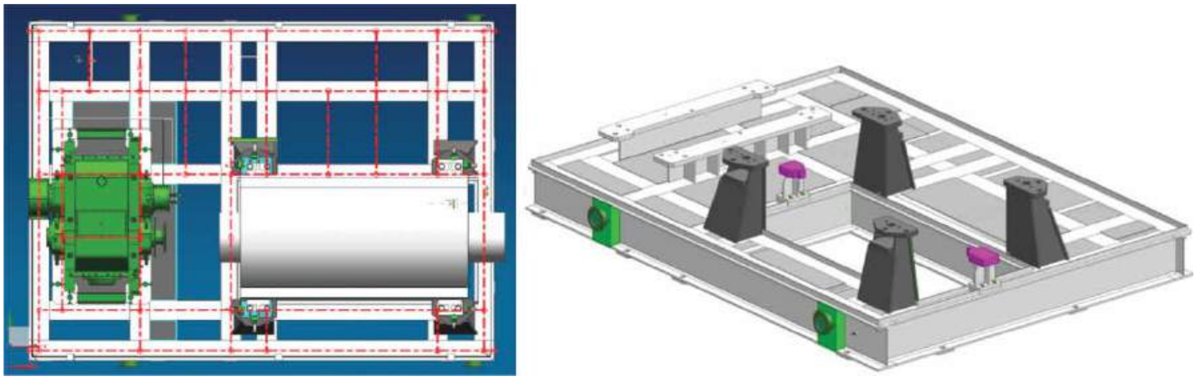

Figure 7. Arrangement of the steelwork baseplate (made of beams and supports to hold the machines).

The engineering cost is defined by parametric formulas, based on the number of modules/functions constituting the product and the number of customizations required to the base product version. The more complex is the product and the more complicated is its engineering. The manufacturing cost calculation has been possible thanks to parametric cost models. Starting from previous design configurations, parametric cost models have been established for each module, in order to link the product/module attributes with the most important manufacturing/assembling operations. For instance, the rotor fabrication depends by its length, diameter, and number of blades (themselves depending by the power). In this way cost models have been detailed along the product development process, from the conceptual design to the detailed design. The installation cost is calculated using empirical tables, where the cost depends by the kind of installation (offshore, inshore, for the baseplate), the weight, and the dimensions.

Finally, the running cost is defined by summing costs for maintenance and energy, calculated for the product lifecycle span, defined on the base of the technological obsolescence. The latter depends by the kind of components (mechanical, electrical, electronic, pneumatic and hydraulic) constituting a specific product or machine. The lifecycle span is calculated multiplying the useful life (determined by historical data) with a factor, from 0 to 1, depending by the kind of components. It is close to 1 for mechanical parts and around 0.5 for electronic ones.

The discount ratio used for cost actualization is a constant value (over the time), but it is customizable by the company according to the specific industrial sector. The maintenance cost actually considers the routine maintenance (planned or for failures management), calculated for the mechanical and electrical/electronic components: the planned maintenance cost item has been calculated considering the plan of operation and maintenance for a similar compressor (same power range). Cost for failures (i.e. part replacement, production standstill, labor, etc.) is estimated with empirical formulas based on the operating time, according to the historical data coming from the service department. The energy cost is estimated according to the use profile of the compressor, which depends by its application (off-shore, inshore) and considers the electric motor features, since motor is the most energy-consuming component. The EoL costs estimation (i.e. cost/revenues for disposal) is still under investigation. The software platform is actually under development in order to test the approach on a wider base of cases.

5. Conclusions

The paper introduced an innovative design-to-sustainability system platform to support designers in rapidly defining optimal design solutions by estimating their impacts in terms of lifecycle costs and environmental footprint. The platform is based on a design approach that combines feature-based analysis and lifecycle cost assessment: it allows the definition of the design structure and its parameters starting from the functional definition of the product, and the impact assessment thanks to parametric models which capture the behavior of the single product parts. Such an approach allows configuring and engineering the desired product according to design specifications and considering both cost and environmental impacts. In this context, the research work focused on gathering data from partner companies regarding product structures, design procedures, cost and environmental impact models, and defined a system framework to support such an approach. Such an approach has been tested on some industrial case studies and an example in the offshore basement configuration and analysis is reported. The outlined platform is currently under implementation and populated with the data from the partner companies in order to test it on more numerous cases. Future works will consist of finding adequate solutions for the efficient implementation of the platform modules, in particular for the knowledge manager and the configuration modules. Then, the platform will be tested and validated on many cases proposed by the industrial partner.

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