Title:
A Design-to-sustainability Platform based on Functional Representations and Simplified Geometric Layouts

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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, optimization in respect with product /system 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 are rather a design output. As a consequence, design is developed without considering such issues and numerous process iterations occur when 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, it is generally managed by inefficient methods and tools. For instance, product cost can be estimated at the beginning of the design process by qualitative methods, but it is deeply analyzed only at the end, when the project is almost conceived, by quantitative estimating techniques [6]. 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 [3].

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: from Design for Manufacturing and Assembly (DFMA) [1] to Feature-Based Costing (FBC) [9], to Design to Cost (DTC) [4], until knowledge-based systems [2, 8]. However, they are usually very complex to use and require a deep knowledge about the related technological background, so they are not suited for designers but rather for skilled 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 poor due to hard implementation, numerous resources to be involved and effort in 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.

<u>The research goal:</u>

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. 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. 1).

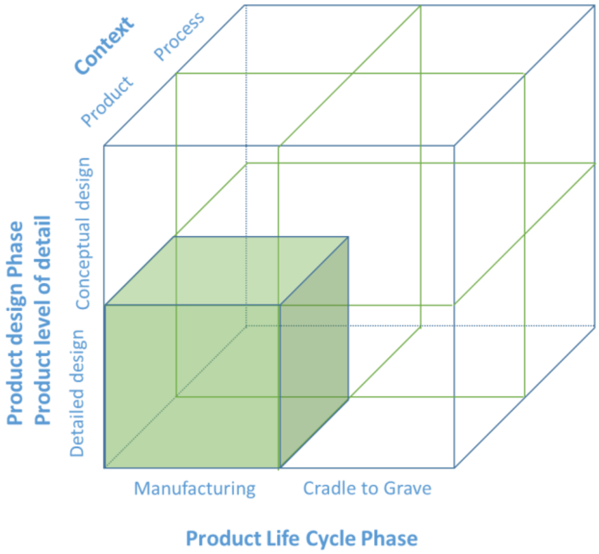

Fig. 1: Extended workspace of the proposed platform (green block highlights the limited operation field of the current cost estimating approaches).

The research defines a specific approach design-to-sustainability that combines a 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; the latter assesses cost and impact of products and processes according to specific cost and impact models covering all the product lifecycle phases. Knowledge-based approaches will be adopted to properly structure the design knowledge and define the models to calculate costs and impacts; furthermore, search and configuration algorithms will be adopted to suggest design solutions in an intelligent way according to the technical specifications, product performances and cost/impact targets. Such an 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.

<u>The solution configuration approach:</u>

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 / Behavioural Structure (FS), an implementation Structure with dimensioning Parameters (SPs) and a Geometrical Elementary Representation (GER). The characteristics of such PDSs are:

- *validness,* 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. it 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.

FS refers to the graph of a group sub-functions connected by flows of material, energy and signal as in the traditional design theory [7], while GER refers to simplified geometric representations made of simple shapes (axis, boxes, cylinders, etc.) and textual or symbolic annotations. In particular, GER aims to represent in the simplest form the embodiment given to a certain FS. A GER represent more sophisticated components with simple shapes while fixing the relevant data which are 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. Starting from a 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 PDS, 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.

<u>The proposed system platform:</u>

The proposed design-to-sustainability system platform is structured in five main modules, which address specific topics and cooperate into unique software architecture to support the designer to define the best design solution according to a set of design drivers. Main 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.

The modules are here briefly introduced (Fig.2):

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

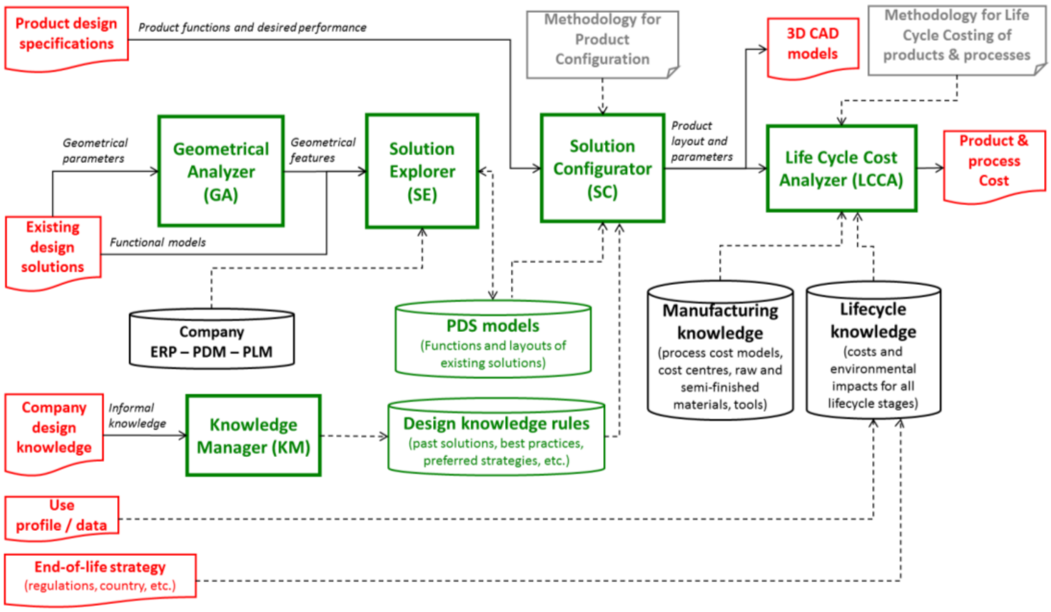

Fig. 2: Design-to-sustainability platform architecture (modules and data flows).

<u>The early assessment of costs and environmental impacts:</u>

The last step of the proposed approach targets a product LCC estimation from its preliminary configuration. LCC estimation is based on parametric cost models of both the manufacturing and End of Life (EoL) phases. Such cost models originate from detailed analysis of existing design solutions; the cost models are then parametrized on the basis of the most relevant design parameters for families of homogeneous solutions. The number of chosen parameters depends on the level of accuracy required by the specific application context. In particular, use-phase cost models mainly includes energy consumption and maintenance cost, which mostly determine the running costs, while EoL cost models mainly consider disassembly and dismantling processes. Specifically, EoL disassembly costs are estimated from disassembly time, which is analytically calculated considering the list of disassembly operations and time required. Moreover, according to the selected EoL scenario, cost models of single operation 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 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 is also used to carry out a simplified environmental Life Cycle Assessment (S-LCA), based on the comparative evaluation among different design solutions in order to define the most feasible one. 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. Finally, the proposed approach can be extended also to production lines in order to estimate the Total Cost of Ownership (TCO) and to support the investment analysis [5]. Indeed, the configuration approach can be used for products as well as for manufacturing process configuration: in this case, the production line, made of sets of machines, is configured according to the product to be processed.

Experimentation and conclusions:

The proposed approach is under experimentation in collaboration with the design departments of several partner companies. In particular the lifecycle of products such as gearboxes, operating machines, cranes and food processing lines have been studied.

The preliminary evaluation of the platform has moved from the functional and modular analysis of the selected products. Then simplified geometrical layouts have been drawn and parameterized. Then new products have been configured following the proposed approach in order to test the feasibility. Since encouraging results have been obtained, the platform is now under development in order to test the approach on a wider base of 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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