Title:

A knowledge-based tool to support the design-to-cost configuration of industrial products from conceptual design stages

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Introduction:

Modern companies are characterized by a growing attention to cost optimization, market needs satisfaction, and time compression at the same time. This trend needs new optimization algorithms integrated with 3D CAD tools able to properly structure the design knowledge and support the designers in configuring the best design solution with respect to desired product performance, required manufacturing processes and production quantities. Such an approach considers cost and performance and could be integrated with also lifecycle assessment (LCA) tools to promote sustainability-oriented design strategies. Indeed, in the modern industrial practice, product cost is estimated at the beginning of the design process by qualitative methods, but is deeply analyzed only at the end of the project by quantitative estimating techniques, when design changes are difficult to implement and very expensive, so that only minor corrective actions can be taken, generating a long iteration loop [7]. Over the last 20 years, some methodologies have been defined to assess cost before product realization in order to optimize product and process design, such as Design for Manufacturing and Assembly (DFMA) approach [1] to Feature-Based Costing (FBC) [14], to Design to Cost (DTC) [4], until knowledge-based engineering (KBE) systems [3, 12]. However, their application in industry is poor due to complex data analysis and knowledge structuring as well we numerous resources to be involved in the project. On the other hand, different approaches like knowledge-based engineering (KBE) [8], artificial intelligence (AI) algorithms [9], object-oriented (OO) design and functional programming [6] have been conceived to easily capture, structure and reuse the design knowledge in a fast and easy way, by automating repetitive tasks and optimization stages.

In this context, the research proposes a knowledge-based tool to model the solutions to be designed into functional modules, to identify the functional features of the product, to represent the product / process-related knowledge according to the design-to-cost approach, and to generate a reliable design solution according to the constraints ah the specific case of application from the conceptual design stages. The paper presents the approach, the prototypal configuration tool, and the results on a set of industrial case studies.

Research approach:

In order to configure a certain design solution according to the design-to-cost principles and the functional requirements of the specific application, the proposed system is based on the functional modeling of the product to be designed, the representation of the company design knowledge, and the selection of the best design solution thanks to AI algorithms.

The first step is about functional modeling. In this context, the scientific literature review provides a broad overview of approaches and methodologies to obtain structured functional representation of a product, with the main scope to offer a wider range of variants and models that can to meet all the consumers' needs [10]. The functional modules able to provide a functional description of a product can be easily identified by the heuristic method proposed by [13]. Furthermore, when the full set of all product components, inputs and outputs is available, it is possible to structuring the product function modules from exploiting Design Structure Matrix (DSM). It allows obtaining a simple, compact, and visually effective representation of a complex system, which can support decomposition and modularization. A product can be easily decomposed into simpler sub-systems and the relationships between the sub-systems as well as input and output data flow can be recorded and monitored. In particular, this research considers the activity-based DSM and parameter-based DSM. The former uses clustering algorithms to group around the functional groups around the diagonal, related to interdependent relations and constraints; they can go to constitute the functional modules from the conceptual design. The latter is time-based and orders the rows and columns through time; it means that upstream entities in a process have to precede the downstream entities, giving added value to the concepts of feedback and feed forward. The parameter-based DSM uses sequencing algorithms to group around the diagonal those product / process parameters that can be configured in a discrete parametric group to appear as an attribute of the product itself.

The second step refers to design knowledge formalization. It is worth to distinguish between explicit or formal knowledge, consisting of tangible and documented information related to both product and processes, and tacit knowledge, which collects all those implicit rules derived from the experience of the designers and the workers that can create further added value to the product itself. Furthermore, a further distinction between product and process knowledge can be made. The former includes all information associated to the evolution of the product during its lifecycle, while the latter involves all those skills in the field of design, manufacturing, and business processes involved in the creation of the product. Finally it can be highlighted further differentiation between compiled and dynamic knowledge: the first category includes the knowledge obtained from experience that allows to obtain explicit knowledge, while the second one refers to a derived knowledge that can generate additional structures to know that lead to implicit knowledge as well. In order to acquire and formalize the knowledge, the research adopts the classification proposed by [2], based on 5 categories: pictorial, symbolic, linguistic, virtual, and algorithmic. The research has been therefore targeted on the implementation of the so-called Function-Behavior-Structure (FBS) design models. These models are able to categorize and describe the product at three distinct levels of details:

1. *Function*: the scope for which the product is made;
2. *Behavior*: how the product actually does;
3. *Structure*: what is the product's physical structure (e.g., parts, connections).

According to [13], it is possible to convert such symbolic description into a geometric description, which provides spatial relationships between objects (i.e., product parts) as a result of the functional relationships. Five basic components can be considered for such mapping: boundary representation (B-Rep), scope of measurement, dimensions, spatial location, and constraints. Such knowledge formalization can be used in combination with DSM approach to define the product function modules and input-output parameters (step 3). However, in order to give a correct functional mapping, a vast database of the product forms, features and constraints has to be set in advance. The main issue in this case is to carry out such an analysis during the conceptual design. Indeed, the tools available to the designers in the early stages of product conceptualization are relatively new, and the majority of knowledge at this stage is tacit, so that its formalization is more difficult with respect to in embodiment and detailed design stages. As a result, conceptual design tools rarely include a robust product formalization to have a practical adoption in the industrial world.

In order to overcome this problem, the proposed approach adds a further step based on the definition of the specific constraint satisfaction problem (CSP) to be solved by AI algorithms. The forth step of the proposed approach refers to the definition of the specific CSP, to easily capture and re-process the corporate knowledge gained over the years and to suggest to the designers effective solutions with a rapid assessment of their associated costs. Indeed, formally a CSP can be defined on a finite set of variables whose values belong to the definition of finite domains and a set of constraints.

A constraint on a set of variables is a restriction on the values that those variables can take simultaneously. Conceptually, a constraint is seen as a set of all the values that the variables can take on at the same time, and that can be represented by means of matrices, equations, inequalities or relations. The approach for the CSP resolution is based on ad-hoc algorithms that compare all found solutions at the same depth (with usually the same cost) to avoid running in infinite paths. In order to avoid the branching factor (at each level of the tree, this factor is in fact equal to the number of variables not yet assigned, multiplied by the number of values that each variable can take), different CSP solvers can be used; in particular Gecode (a toolkit for the development of "constraint-based", systems and applications), MiniZinc (a modeling language to mid-level constraints, which exploits the advantages of a library of pre-defined constraints), Cream (a Class Library for Constraint Programming), Jacop (a Java-based constraint solver), or Choco (a free Java library dedicated to Constraint Programming).

The last step refers to the design solution configuration, which exploits the company knowledge formalization to define a cost function for the different product modules. It starts from the acquisition of the historic company data as well as the human experience matured during the years in order to define a cost function for the main product modules based on the design process output parameters. Knowledge formalization by a PDM-PLM system or other data storage systems in the company can be very useful to shorten the preliminary phase. The analysis of the historic data can start with the choice of a family of products for which you collect customer specifications, BOM, design documents, drawings, and cost information. Such data must be properly organized and classified. It is important to select products that are very different from each other, so you can consider all possible relations between functions and customer requirements. After data collection, the conversion of the product requirements into a functional structure is required. It is advisable to concentrate on product linked by developing a requirements-based functional model. In this way the requirements can be easily connected to the physical blocks of the product (modules). As a result, the functional groups of the product identified by DSM can be identified, configured and related to costs. IDEF diagrams are used to identify the most important parameters of each module and to dimension it, considering its input and output. For the resolution of dependencies between activities a DSM is used at different levels. By means of partitioning algorithms, activities and parameters can then be rearranged in order to minimize the cost. Cost models are defined according to analytic approach according to [3].

The research approach can be synthetized in the following steps:

1. Identification of the product functional structure, according to the heuristic method proposed by [11];
2. Formalization of the design knowledge, including the formalization of explicit and tacit knowledge related to the product based on the company best practices as well as the human expertise;
3. Definition of the product function modules and input-output parameters, where dependencies are defined by design structure matrix (DSM) approach, in particular activity-based DSM and parameter-based DSM;
4. Definition of the specific constraint satisfaction problem (CSP), to easily capture and re-process the company knowledge to suggest effective solutions considering the possible product alternatives with their associated costs;
5. Dimensioning of the product modules and configuration of the optimized solution:

<u>The product configuration tool:</u>

The configuration software tool includes three different interfaces, which respectively represent the product according to its functions, modules, and physical components. In this way it allows to design a new product from a functional viewpoint by defining its functions into modules, and subsequently define its architecture by connecting the defined functions. It allows respecting the product modularity also into the architectural design. Furthermore, in order to reuse the company knowledge for the new product design by using already-implemented technical solutions, a search function has been implemented. Indeed, in order to generate a quotation on the basis of specific technical requirements for the customers, it is possible to search for similar product specifications, filter according to product characteristics, and explore past products with different features and compare. Past solutions can be compared with the new one by a similarity measure based on the Minkowski formula [11]. After having selected past products, it is possible to retrieve the technical solutions used and adapt them for the new product. Both fully pre-existing products with the same attributes, the same geometry, etc., and new block instance with different geometry and/or attributes modified to meet the specifications can be used. The cost information of previous solutions can be used to estimate at an early stage of the new product, by properly adapting by means of parametric formulas based on modules attributes.

Industrial case study:

The approach has been tested on the "bridge cranes" product family in collaboration with an Italian company that manufactures lifting equipment. For this specific product family, a set of product information was retrieved, organized and classified: i.e., customer specifications, BOM, design documents, 3D models, 2D drawings, and cost data. While working on a single product type (the crane), the different specifications and customer requirements make it different from every other machine. Indeed, those machines are used in several plants (i.e., cement plants, power plant, nuclear, waste pit). In order to consider all possible combination of functions and customer requirements, a general functional model for the bridge crane was defined. After that, the activity-based DSM allowed grouping the tasks in a logical sequence of execution and identifying the activities, and the parameter-based DSM allowed identifying the parameters affected by mutual dependence and their reciprocal order. In this way the implicit knowledge from designers, who implicitly know when a parameter has to be defined along the design process, was captured and formalized.

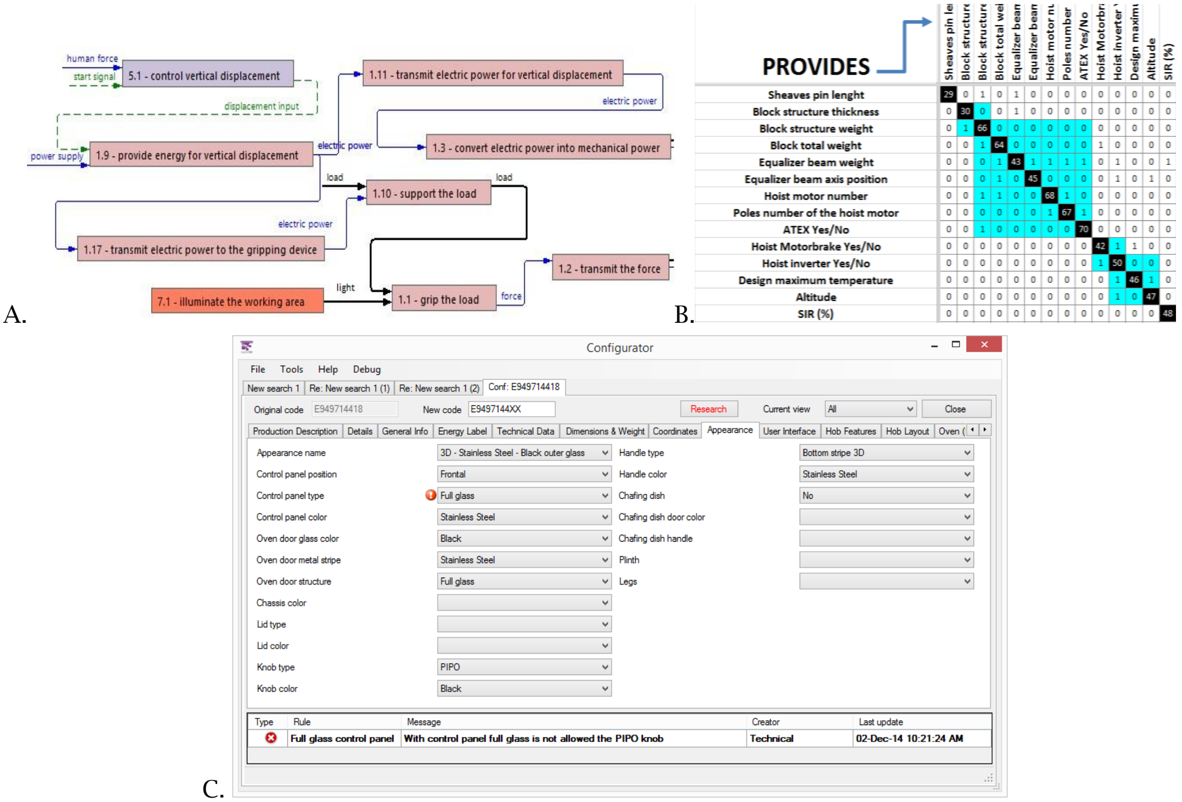

Fig. 1: Case study for approach and tool validation: functional general model for the bridge crane (A), reordered DSM by means of partitioning algorithms (B), and tool interface for solution search and parameters-based configuration (C).

Conclusions:

The research focuses on the definition of a knowledge-based tool to support the design-to-cost configuration of industrial products according to the specific design constraints and customers' requirements. 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. The main contributions of the research are: the definition of a new methodology to formalize the company design knowledge and to combine it with the creation of the product functional structure considering technical requirements as well as cost constraints, and the development of a new software tool to easily implement such methodology and configure the product modules' according to optimization algorithms. Such a tool can be also integrated to 3D CAD systems to automatically configure 3D product models on the basis of the company knowledge.

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