Title:
A CAD-based Method for Multi-objectives Optimization of Mechanical Products

Authors:
Vincenzo Castorani, v.castorani@pm.univpm.it, Università Politecnica delle Marche
Alessio Vita, a.vita@pm.univpm.it, Università Politecnica delle Marche
Marco Mandolini, m.mandolini@univpm.it, Università Politecnica delle Marche
Michele Germani, m.germani@univpm.it, Università Politecnica delle Marche

Keywords:
Design for Cost, CAD parameterization, Multi-Objective Optimization.

DOI: 10.14733/cadconfP.2016.168-172

Introduction:

Complex dynamics of global markets force companies to adopt new ways in order to increase competitiveness. The multidisciplinary approach has proven to be crucial in making products always more competitive and successful. When tackling issues increasingly complex, the designer is obliged to consider simultaneously multiple perspectives in order to determine the optimal solution. Engineers are asked to achieve the right compromise in terms of product features to optimize the product performances, manufacturing cost and manufacturing lead-time.

This optimization process is often manual [10] and does not allow a comprehensive exploration of what the main problem is, leading to the choice of solutions that are potentially suboptimal. Furthermore, objective functions often cannot be expressed through the use of simple algebraic relations which necessarily bring up the need of using specific software for their evaluation. Moreover, a step-by-step approach to identify the right combination of design criteria is a time and cost consuming process. Therefore, the automation of the optimization process, based on the integration of CAD, CAE and Design for Cost (DfC) software, is essential to increase the product quality and to facilitate and accelerate the identification of the optimal configuration.

The most used CAD-CAE-DfC tools available on the market are stand-alone systems, which need a relevant user interaction for achieving a real integrated use [7,8,12]. Moreover, even if integrated software exist (such as SolidWorks), designers tend to use CAD tools for product modeling and other commercial CAE and DfC tools for the specific analysis [9].

CAE software tools with optimization modules capable to work with parameterized CAD models, are widespread. Through these modules, it is possible to set constrains that have to be respected and goals that have to be achieved in order to automatically identify the best configuration. However, no economic optimization is taken into account.

Today the need to get information about product manufacturing time and cost in a quick and accurate manner has led to the development of DfC software (Design for Cost). DfC tools, due to internal algorithms, are able to determine machining cycles and machine tools required to produce a part respecting prescribed roughness and tolerance. Furthermore, assembly features, such as weldings and couplings, can be automatically recognized by analyzing 3D assembly models. However, none of this software contains features for a multi-objective optimization process.

In literature, it is possible to find numerous approaches for the design and optimization of products. Nonetheless, in general, the focus of these approaches is the product performance without any consideration about manufacturing time and cost.

The multi-objective optimization is a consuming process from a computational point of view due to the complexity of the FEA codes and the cost assignment process [13]. The general approach used to reduce the computational cost consists in making a limited number of simulations based on the Design Of Experiment (DoE) method [1,2,4,5]. The simulation results are used to realize an approximated model of a system response through the Response Surface Methodology (RSM) [3]. The approximated model is called "surrogate model" or "metamodel" and can be generated using different techniques [11]. From the surrogate model it is possible to analyze thousands of configurations that identify, through the support of appropriate optimization algorithms, the optimal one. With optimum configuration we refer to the procedure that reaches the right compromise between objectives, that can also be conflicting, and that does not violate the fixed constraints.

In this context, this paper aims to develop a methodology that allows, through the effective integration of different design and simulation tools, the product multi-objective optimization considering also manufacturing time and cost. The CAD system is the main actor of this process since it is able to interconnect both the CAE software and the DfC software for the specific analysis. In addition, thanks to the possibility of parameterizing the geometric model, it is possible to use an optimization tool that enables to vary design criteria in an automated way, allowing the analysis of numerous configurations and the identification of the optimal one, without any interaction with designers.

Main idea:

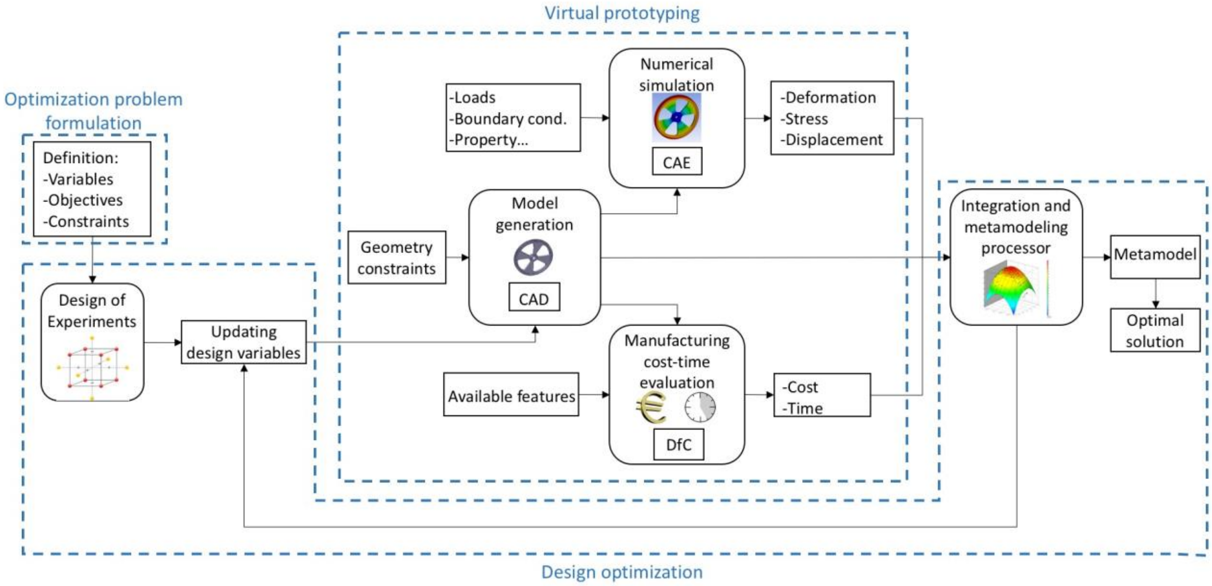

Fig. 1: CAD based method for multi-objectives optimization.

This paper presents a methodology (shown in Fig. 1) to support the designer in determining the design parameters, which guarantee the best product performance, while minimizing manufacturing cost and time. This methodology, combining opposing objectives and considering constraints defined by the designers, allows coping with the complexities faced in the process of multi-objective optimization, taking into account multidisciplinary problems.

The proposed methodology integrates three different levels of analysis: optimization problem formulation, virtual prototyping and design optimization.

The first step of this methodology consists in formulating the optimization problem by specifying the objectives, constraints and design variables. The formulation of the optimization problem is a key level of the presented methodology and it is complementary to the design optimization level. Indeed, an inadequate formulation typically leads to wrong conclusions. It is necessary to define the formulation model reflecting the situation being modeled, with a reasonable resources consumption. In formulating the optimization problem, designers must choose the variables to investigate, the objectives to achieve and the constrains to satisfy. The variables to optimize may be many and various: size, geometry, material, tolerance etc. The number of these variables can be very high. The designers have the task to reduce this number in order to have a good compromise between accuracy and speed. Usually, there is not only one possible goal but designers have to choose from a variety of different goals. An important aspect of problem definition is the selection of relevant objectives and, if necessary, to assign them with an importance rate. The more decision alternatives designers have to consider, the more difficult it is to choose a proper alternative. Constrains specify the restrictions and interactions that limit variable values, CAE simulation and time and cost of manufacturing.

The virtual prototyping level employs modeling and numerical simulation techniques to develop a digital model of the product, containing as many product and process information as possible, necessary for its production, in order to allow performance, economic, aesthetic and, if necessary, ergonomic evaluation. In this level, three classes of software tools must be used and integrated among them:

1. CAD system for three-dimensional geometric modeling;
2. Product simulation system (CAE);
3. System for the manufacturing costs and times evaluation (DfC).

The first step of this level consists in the CAD model generation with the geometrical and non-geometrical parameterization according to chosen design variables. In this phase, engineers define also the product characteristics necessary to the next analysis: materials, roughness, tolerances etc. The subsequent step consists, through CAE and DfC tools, in the product performance and manufacturing cost and time evaluation.

The Design Optimization level guides the analysis of virtual simulations by identifying a certain number of parameters, which influence system response. Through the construction of the response surface, it is possible to analyze the behavior and manufacturing cost and time of the product in all operating conditions. The DoE method provides the experiment plan definition related to the parameters chosen in virtual modeling. The engineer can use his know-how to set the parameter range and to evaluate the most suitable configuration. According to DoE approach, a reduced number of experiments is required to elaborate the final optimum condition. Each test includes a combination of the set of values in order to investigate the influence of each parameter. At the end of this level the model optimal configuration is found. To support this phase on the market are available software that allow the product multi-objective optimization.

This approach fully exploits the ability to configure the CAD model in order to allow its integration with other software tools. The optimization software defines the DOE, manages all the connection between CAD-CAE-DfC software and allows to fully automate the process. Furthermore, it allows to analyze the results in order to choose the best solution through different methods.

Case study

In order to facilitate the understanding of the proposed approach, a case study will be presented and discussed. This method has been used to redesign the modular structure used for the rotation of the armchairs under the floor level (to hide it), with the objective to manufacturing cost and time. An Italian leading company in the production of sofas and armchairs actively participated at the test of the proposed method.

The product is made up of commercial and machined parts, for a total of about 300 components. The existing product has been analyzed by the design team in order to identify both the economic and functional system weak points.

During the redesign phase, designers proposed different possibilities for the resolution of the design criticalities, which have been subjected to a technical and economic assessment to be validated.

In order to find the optimal solution, the method previously described has been used by setting the most relevant parameters concerning the CAD model. Among these parameters there are, for example, the diameter of the shafts, the thickness of the sheetmetals, the modules of the toothed wheels, fillet radius etc. The CAD model has been analyzed with a FEM software (ANSYS® Workbench®) to examine the structural behavior and with a DfC tool (LeanCOST® by Hyperlean®) to evaluate the manufacturing cost and time. The automatic integration of these software tools and the changing of the CAD model parameters has been handled by the optimization software modeFRONTIER® (by ESTECO®), as shown in Fig. 2. It firstly creates a DOE with the geometric and non-geometric variables of the model and then generates a metamodel using response surface methodology with the structural results as well as manufacturing time and cost. Lastly, through specific optimization algorithms, it is possible to proceed with the determination of the optimal solutions.

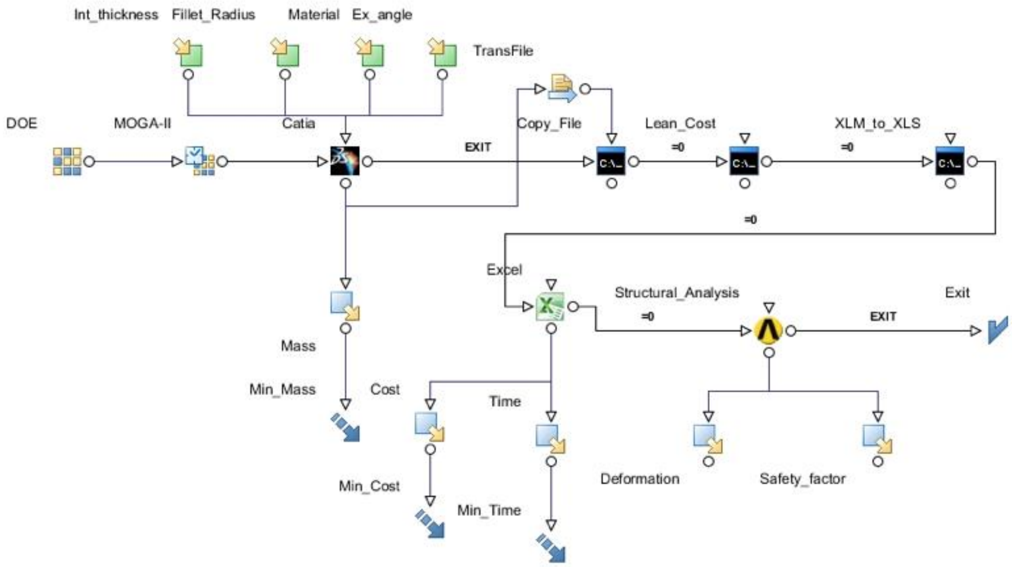

Fig. 2: Workflow of the optimization process for a part.

The optimal solution shown by the software tool was validated by specific simulations to verify that it is not subject to errors regarding the regression of response surface.

The presented methodology has been used in a case study and it has been compared with the traditional (manual) optimization process. Two design teams carried out the same optimization analysis of the modular structure, the first (two engineers) using the presented methodology, and the second (three engineers) following the traditional method. The aim was to test the functionality of the automated process and to compare the results achieved. The team that used the mentioned approach was able to identify the optimal solution, saving 13% of manufacturing cost and 17% of manufacturing time, compared to the solution achieved by the other group.

Conclusions:

The paper presented an optimization method for supporting the definition of the design solution optimizing an objective function while respecting the constraints imposed. This method is based on a parametric CAD system and FEM and DfC software tools respectively for multiphysics and manufacturing cost and time analysis. By linking these systems with an optimization software, it is possible to seek automatically the parameters of the CAD model that allow to reach specific goal/s.

The presented methodology has been designed to be used both for the study of a single component and for complex assemblies. The latter enables designers to focus on the global analysis of the system and not only on the individual parts. Thus, the use of this method leads to a significant time saving and it allows to evaluate a number of configurations that otherwise would not be possible to consider. However, it is not possible to choose a number of variables that is too vast because of the metamodel limits [6]. In addition, the analysis of complex systems, especially for FEM simulation, requires a considerable computational effort and therefore limiting the considered design variables turns out to be a winning strategy to save time and costs. It is up to the designer, through a proper correlation analysis, to limit the number of design variables only to those that have a greater impact on fixed goals.

Future works will be focused on the study of methodologies to support designers in detecting the low impacting variables that can be neglected by the optimization analysis, in order to save the computational resources. This improvement will allow designers to reduce the time for the configuration of the analysis.

References:

[1] Blondet, G.; Belkadi, F.; Le Doigou, J.; Bernard, A.; Boudaud, N.: Towards a Knowledge based Framework for Numerical Design of Experiment Optimization and Management, Computer-Aided Design and Applications, 7, 2015, 71–86.

[2] Box, G.E.P.; Hunter, S.J.; Hunter, W.G.: Statistics for Experimenters: Design, Innovation, and Discovery, 2nd edition ed., Wiley and sons, 2005.

[3] Box, G.E.P.; Draper, N.: Response Surfaces, Mixtures, and Ridge Analyses, John Wiley and Sons, 2007. http://dx.doi.org/10.1002/0470072768.

[4] Hatami, M.; Jafaryar, M.; Ganji, D.D.; Gorji-Bandpy, M.: Optimization of fined-tube heat exchangers for diesel exhaust waste heat recovery using CFD and CCD techniques, Int Commun Heat Mass Transfer, 57, 2014, 254–263, http://dx.doi.org/10.1016/j.icheatmasstransfer.2014.08.015.

[5] Hatami, M.; Ganji, D.D.; Gorji-Bandpy, M.: Experimental and numerical analysis of the optimized finned-tube heat exchanger for OM314 diesel exhaust exergy recovery, Energy Convers Manage 97, 2015, 26–40. http://dx.doi.org/10.1016/j.enconman.2015.03.032.

[6] Jin, R.; Du, X.; Chen, W.: The use of metamodeling techniques for optimization under uncertainty, Struct Multidisc Optim, 25, 2003, 99–116. http://dx.doi.org/10.1007/s00158-002-0277-0.

[7] Park, H.S.; Lee, G.B.; Kim, H.: Collaborative engineering system supporting product development process. In: ASME design engineering technical conferences, Chicago, USA, vol. 1, Part B; 2003, 873–80, http://dx.doi.org/10.1115/detc2003/cie-48267.

[8] Park, H.-S.; Dang, X.-P.: Structural optimization based on CAD–CAE integration and metamodeling techniques, Computer-Aided Design, 42(10), 2010, 889-902. http://dx.doi.org/10.1016/j.cad.2010.06.003.

[9] Riesenfeld, R. F.; Haimes, R.; Cohen, E.: Initiating a CAD renaissance: Multidisciplinary analysis driven design - Framework for a new generation of advanced computational design, engineering and manufacturing environments, Computer Methods in Applied Mechanics and Engineering, 2015, 1054–1072. http://dx.doi.org/10.1016/j.cma.2014.11.024.

[10] Roy, R.; Hinduja, S.; Teti, R.: Recent advances in engineering design optimization: challenges and future trends, CIRP Annals-Manufacturing Technology 2008, http://dx.doi.org/10.1016/j.cirp.2008.09.007.

[11] Simpson, T.W.; Peplinski, J.D.; Koch, P.N.; Allen, J.K.: Metamodels for computer based engineering design: survey and recommendations, Engineering with Computers, 17, 2001, 129-150.

[12] Tsuen, B.; Lin, C.; Kuo, C.: Application of an integrated CAD/CAE/CAM system for stamping dies for automobiles, Int J Adv Manuf Tech, 35, 2008, 1000–1013, http://dx.doi.org/10.1007/s00170-006-0785-y.

[13] Wang, G.G.; Shan, S.: Review of metamodeling techniques in support of engineering design optimization, Journal of Mechanical Design, 129(2), 2007, http://dx.doi.org/10.1115/1.2429697.