From Computer-Aided (Detailed) Design to Automatic Topology and Shape Generation

Chapter 2
From Computer-Aided (Detailed) Design to Automatic Topology and Shape Generation

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Abstract This chapter surveys the evolution of Computer-Aided systems in terms of support to the earliest stages of design and more specifically to the embodiment design phase, when functional requirements and related structural and manufacturing constraints must be translated into a working solution, i.e. the generation of topology and shape of a mechanical part. After an introductory discussion about the context and the limitations of current systems, the chapter summarizes the research outcomes of two projects: the first, namely PROSIT (From Systematic Innovation to Integrated Product Development), aimed at bridging systematic innovation practices and Computer-Aided Innovation (CAI) tools with Product Lifecycle Management (PLM) systems, by means of Design Optimization tools. The second, coordinated by the authors, is a prosecution of PROSIT and proposes the hybriDizAtion of Mono Objective optimizations (DAeMON) as a strategy for automatic topology and shape generation. The latter is clarified by means of two exemplary applications, one related to a literature example about Genetic Algorithms applied to multi-objective optimization, the second to an industrial case study from the motor scooter sector.

2.1 Introduction

The last century has seen the development of more and more structured methods and procedures to support the Product Development cycle, both in terms of techniques to guide designers' decisions and of technologies to aid analysis and synthesis tasks. Three main ages are recognized in literature [1]: the era of productivity characterized by an increase of demand by society for the acquisition of

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technical objects and consequently the focus on productivity improvement and costs reduction; the era of quality characterized by the necessity for rigorous steps of measurement and monitoring the production in order to increase the profitability, towards a total strategy of optimization of its efficiency; the era of innovation characterized by the need for structuring not only productivity and total quality, but also building a strategy of systematic innovation to bring in the market products addressing new users' needs or new ways to satisfy already identified needs and requirements.

The first two ages have firstly involved the optimization of the production departments (both methods and technologies) in order to reduce the unitary cost of a product, i.e. adopting lean production approaches, and to guarantee its quality, i.e. ensuring the robustness of the related manufacturing processes.

More recently, the focus has been switched to the engineering design tasks since they dramatically impact costs and quality, but also due to the emergence of innovation as the key for being competitive in the global market.

Despite methods and tools for engineering design have radically evolved in the last decades also thanks to the availability of computational resources not comparable with any human effort, the engineering design process can still be considered as a series of three major stages: conceptual design, embodiment design, and detailed design [2].

Pahl and Beitz consider conceptual design as ''a search across an ill-defined space of possible solutions, using fuzzy objective functions and vague concepts of the structure of the final solution''. According to this classification, embodiment design operates with a selected (during the conceptual design stage) initial design configuration and aims to further specify the subsets form in the whole system.

Nevertheless, in order to be competitive in current markets, companies must combine the capability to propose innovative products and services with efficient development processes. In this perspective, the authors think that the vision of Pahl and Beitz on conceptual design needs to be updated, since a proper identification of the design goal, as well as a formalization of the project constraints, are necessary to reduce, since the very beginning of the innovation process, waste of time and resources through useless trials and errors.

Besides, the efficacy and the efficiency of the innovation process are highly impacted also by the adoption of suitable methods and tools in the embodiment design stage, i.e. that part of the design process in which, starting from the working structure or concept of a technical system, the design is developed, in accordance with technical and economic criteria, to the point where subsequent design can lead directly to production [2].

Therefore, a crucial objective to be pursued is the development of means to support synthesis design tasks and not only the analysis of solutions generated upon the intuition and the experience of senior designers, since in modern organizations all the employees should bring a creative contribution to value creation.

The present chapter aims at presenting the authors' experience and vision about the evolution of Computer-Aided systems with respect to synthesis design tasks, with a specific focus on the embodiment of mechanical parts starting from the functional requirements and the related structural and manufacturing constraints.

The next section of the chapter is dedicated to an overview of the related art with the aim of highlighting technological resources as well as the limitations of current systems. The third section presents the outcomes of a research project (namely PROSIT) aimed at integrating Computer-Aided Innovation systems with PLM tools, while the following proposes the prosecution of the PROSIT project developed by the authors, aimed at embodiment design automation through topological hybridization of partial solutions. The last section proposes a discussion on the expected trends of evolution in this domain and the conclusions of the chapter.

2.2 Related art

The related art here presented is divided in two subsections, the first dedicated to a brief survey on the role of computers for product development, the second focused on the description of optimization techniques in the field of Computer-Aided Design.

2.2.1 The role of computers in the early phases of the product development cycle

Computers have gained more and more importance for product development since the dissemination of the first CAD systems prototypes in aerospace industry. Nowadays, they play a crucial role in any industry in detail design tasks, as well as for planning production activities. The so called PLM (Product Lifecycle Management) systems claim to support any stage of Product Development. In fact, they are extending their domain of application upwards the preliminary phases of design and by embedding more abstract representations of the product (fig. 2.1, continuous arrows), but still they are far from systematizing inventive design phases and the link between the development of a conceptual solution and the definition of the product geometry. Indeed, despite it is widely recognized the relative importance of conceptual design, due to its influential role in determining product's fundamental features, as a matter of facts, CAD/CAE systems are not conceived to allow fast input and representation of concept models, and consequently they introduce inertial barriers in experimenting new models of design solutions. Indeed they don't provide any support to designers in developing and expressing their creativity [3,4].

Recently, Computer-Aided Innovation (CAI) systems have started addressing these lacks [5], trying to leverage the potential of TRIZ [6], the Russian theory for inventive problem solving which constitutes the foundational pillar for most of the

CAI software systems. Besides, the domain borders of this emerging technology are still fuzzy and in any case CAI systems suffer of limited interoperability with downstream CAx tools [7].

Thus, a relevant research topic to improve the efficiency of the innovation process is the development of computer-based means for bridging conceptual design with existing PLM systems and the detail design phase, i.e. the extension of the CAI domain towards the embodiment design (fig. 2.1, dashed arrows).

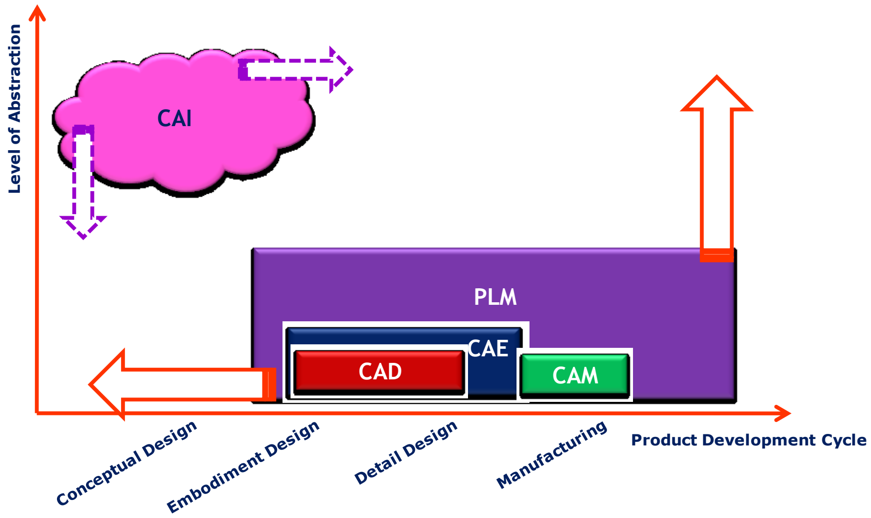

Figure 2.1 Application domain of computer-based tools within the Product Development cycle.

It is worth to mention that a few preliminary experiments to embed the principles of TRIZ within CAD systems have been attempted with promising, but still not satisfactory, results [8-10]. The main limitation stands in the distance between product models in these two different categories of systems: CAI systems need a more abstract representation, function- or requirement-oriented, with fuzzy topology and/or shape; besides, PLM systems are all structured assuming a more detailed representation of the product, in most cases with explicit geometry and limited possibilities to introduce variations through the control of pre-defined parameters.

A different approach to bridge CAI and PLM systems has been proposed within the PROSIT project [7], whose main outcomes are described in the section 3 of this chapter. The logic of PROSIT is to adopt the geometry generation capability of topological optimization systems (briefly overviewed in the next section) as a means to translate the CAI output into a product model manageable by currently available PLM systems. The authors have further developed this concept by developing a semi-automated procedure for conducting the embodiment design phase, through the hybridization of mono objective optimizations, as described in section 2.4.

Let's consider again the description of the embodiment design phase proposed in [2]: embodiment tasks involve a large number of corrective steps in which analysis and synthesis constantly alternate and complement each other. It is evident that those iterations negatively impact the efficiency of the whole design process, thus a relevant objective for a new method is reducing the need of corrective steps.

According to Kicinger et al. [11] Computer-Aided optimization systems are candidate means to improve design efficiency, thus from this point of view supporting the intuition of the PROSIT project; besides, they claim that topology, shape and size optimization systems can respectively address the needs of conceptual, embodiment and detail structural design. Nevertheless, according to the optimization logic, conflicting requirements are approached looking for the best compromise solution, referred as optimal. Vice versa, it is necessary to highlight that compromise solutions typically are less competitive and have a shorter perspective since, according to TRIZ, technical systems evolve by overcoming, and not compromising, contradictions [6]. It is clear that overcoming contradictions is essential in conceptual design, but avoiding compromise solutions in the embodiment design phase allows to properly exploit valuable concepts.

In conclusions, a straightforward introduction of optimization systems in the product development cycle, even if beneficial for the efficiency of the process, can worsen its effectiveness by pushing the designer to the development of compromise solutions. From this point of view, the development of Computer-Aided systems capable to support the creation of design embodiments beyond the adoption of trivial compromises is a relevant goal for extending the potentialities of CAI systems. According to this statement, the chapter describes an original approach to geometry definition which, despite not involving any inventive act by the designer, is capable to suggest a reduced number of potential topologies and usually results more effective than traditional optimization algorithms.

2.2.2 Design optimization systems

Designing by optimization techniques means translating a design task into a mathematical problem with the following basic entities:

- An objective function, i.e. the performance of the system that the designer wants to reach or to improve;
- A set of design variables, i.e. the parameters of the system affecting the objective function;
- A set of loading conditions and constraints representing the requirements the system has to satisfy.

The optimization algorithm finds the value of the design variables which minimizes, maximizes, or, in general, "improves" the objective function while satisfying the constraints.

The synthesis of product geometry from its functional architecture is an extended perspective for optimization systems; in [9] shape and topological variations of a 3D model are proposed as a means to generate an optimal geometry through the application of Genetic Algorithms (GAs in the following). Nevertheless, topological and shape variations are obtained through the modification of classical 3D modeling features, which dramatically limit the design space and impact the practical usability of the proposed method.

The typical classification of optimization systems according to the problems they approach is reported in [11]:

- Topology (layout) optimization, also known as topological optimum design, looks for an optimal material layout of an engineering system;
- Shape optimization seeks optimal contour, or shape, of a structural system whose topology is fixed;
- Sizing optimization searches for optimal cross-sections, or dimensions, of elements of a structural system whose topology and shape are fixed. It is worth to add that a more general definition of this last class of systems refers to parametric optimization, since also other properties of the elements can be assumed as design variables, e.g. the material properties.

Topology Optimization [12] has received extensive attention and experienced considerable progress over the past few years to support design tasks related to the embodiment of functional schemes. It was developed in the structural field but recently it has been applied to address design problems also in other fields such as: fluid dynamics, heat transfer and non linear structure behavior: examples of these novel applications of topological optimization can be found in [13, 14].

Topology Optimization determines the optimal material distribution within a given design space, by modifying the apparent material density assumed as design variable. The design domain is subdivided into finite elements and the optimization algorithm alters the material distribution within the design space, according to the Objective and Constraints defined by the designer. The Objective is constituted by one or more system performances that the optimization should improve. Each system performance is quantitatively assessed by an evaluation parameter that is assumed as metric. According to this statement, a mono-goal optimization task tries to improve a single system performance, while a multi-goal optimization task aims at improving a combination of performances. The constraints of the optimization task represent the operating conditions and the requirements the system has to satisfy. Among them, manufacturing constraints may be set in order to take into account the requirements related to the manufacturing process. Also the regions of the design domain defined as “functional” by the designer, are preserved from the optimization process and considered as “frozen” areas by the algorithm. The topology at the end of the optimization process is identified by filtering the resulting material density distribution through a proper threshold having a value included within the interval (0,1)

Until now, several families of structural topology optimization methods have been developed, a wide literature review is presented in [15].

One of the most established families of topology optimization methods is based on the so called SIMP approach where SIMP stands for Solid Isotropic Material with Penalized intermediate densities [16, 17]. It uses a gradient based approach to search the optimal material distribution within the design domain. Thanks to its computational efficiency and conceptual simplicity it has gained a general acceptance in recent years and it is extensively used in the commercial software. The SIMP method is able to deal with optimization problems having a combination of a wide range of design constraints, multiple applied loads, and very large 3D systems. However, as proved by several papers as [12], SIMP gives solutions near to the global optimum only when the optimization problems are convex problems such as those related to the improvement of only one performance of the system (a classical example of an optimization convex problem is represented by the minimization of the compliance of a structure that experiences only one load condition). Unfortunately it is not able to deal with non-convex problems such as multi-objective optimization tasks that are typically related to the improvement of two or more performances of the system. In such cases SIMP could bring to local optimal topologies or converges to an infeasible, i.e. not manufacturable solution. This drawback is common to all the optimization methods based on the mathematical gradient approach.

Instead of searching for a local optimum, one may want to find the globally best solution in the design domain. For this purpose GAs have become an increasingly popular multi-objective optimization tool for many areas of research. More recently, GAs have been gradually recognized as a powerful and robust stochastic global search method for structural topology optimization [18-20]. Besides, in order to guarantee the robustness of the solution, GAs require more computational resources than the mathematical methods based on the gradient approach. This is due to the high number of design variables that are typically involved in the topology optimization task and this is the main reason such that GAs still have not been implemented in commercial CAE tools [21]. Studies on GAs for topology optimization have been performed in recent years, but these attempts are referred to relatively small problems, such as optimization of truss systems with few design variables [22, 23] or 2D problems [24]. Moreover due to the stochastic searching nature of GAs, structural connectivity cannot be guaranteed; this is another main drawback for the application of GAs for topology optimization tasks.

The above literature review shows that the topology optimization techniques based on the mathematical gradient approach are more efficient than GAs from a computational point of view, but they often bring to local optimum solutions when complex engineering problems have to be solved. Besides GAs present a high robustness in finding global optimal solution for multidisciplinary problems even if they are not able to deal with a high number of design variables, such as that commonly involved in topology optimization.

However, since the design process has multidisciplinary characteristics, it implies that improving one performance of a system often may result in degrading another. Such kind of conflicts cannot be solved using topology optimization techniques based on the gradient approach since they are able to focus the design task only to one specific performance to be improved. Besides GAs are design optimization tools that allow to manage multiple goals just by defining complex multi-objective functions but this task requires the definition of a weight to be assigned to each specific goal [25]. Thus, the best compromise solution is generated on the base of an initial assumption made by the designer about the relative importance of the requirements, without taking into account the reciprocal interactions.

2.3 Integrating Computer-Aided Innovation with PLM systems: the PROSIT project

As briefly introduced in the previous section, the PROSIT project (www.kaemart.it/prosit), "From Systematic Innovation to Integrated Product Development", aimed at bridging systematic innovation practices and Computer-Aided Innovation (CAI) tools with Product Lifecycle Management (PLM) systems, by means of Design Optimization tools.

The goal of PROSIT was to demonstrate that is possible to define a coherent and integrated approach leveraging on available theories, methods and tools as illustrated in Fig. 2.2.

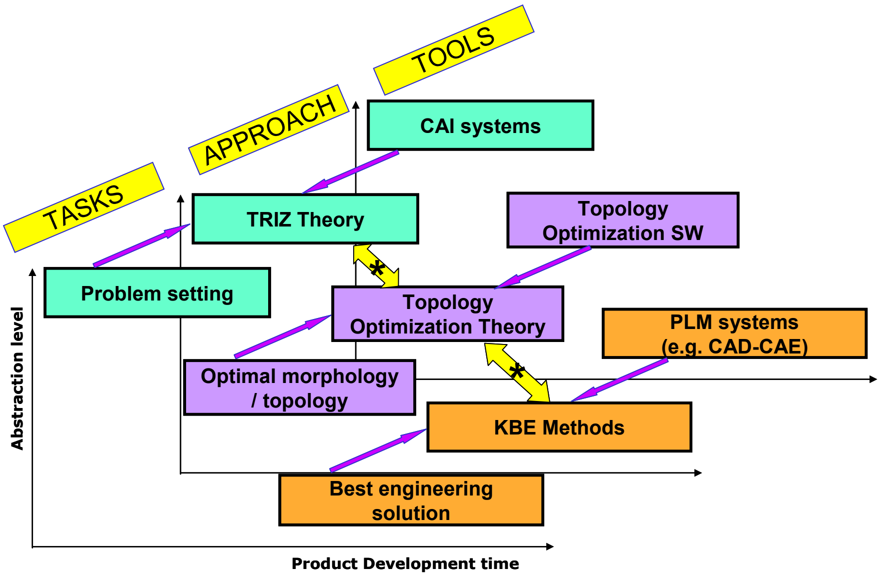

Figure 2.2 Layered representation of approach/methods and tools supporting the problem solving tasks of a product development process

The rationale behind the adoption of Optimization systems as a bridging means is the following:

- defining a single multi-objective optimization problem leads to a compromise solution;
- besides, defining N complementary mono-objective optimization problems, each with specific boundary conditions, leads to N different solutions;
- these solutions can be conflicting and this is the key to find contradictions to be overcome according to the principles of TRIZ.

According to this statement, the PROSIT design flow is structured as depicted in Fig. 2.3. The process starts with the definition of a multi-objective optimization analysis; if the results satisfy the whole set of constraints and requirements the designer can proceed towards the detailed design of the product. Besides, if the output of the multi-goal optimization doesn't fit the product specifications, a set of single-goal optimization tasks, each representing a specific operating condition and/or a given design requirement, must be defined.

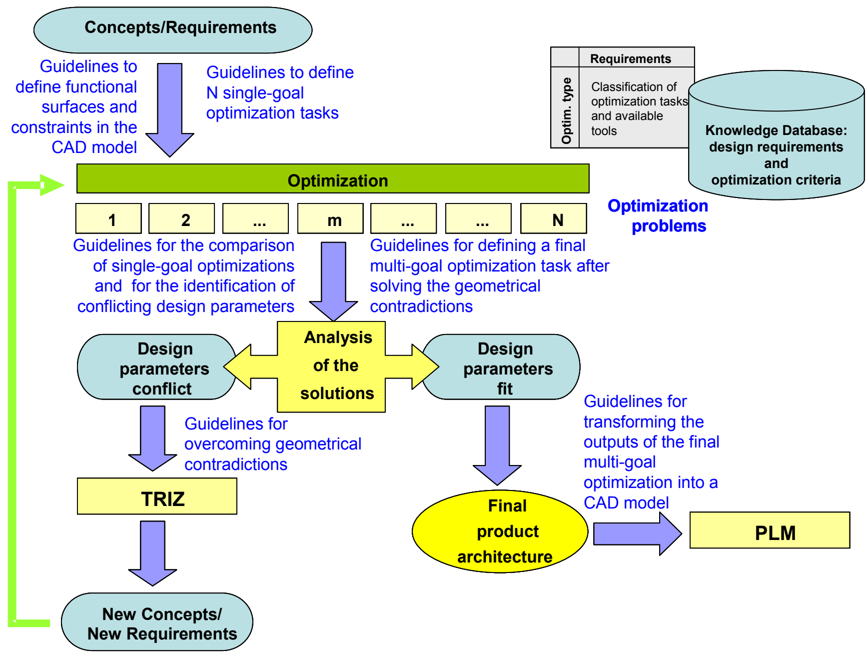

Figure 2.3 Design flow according to the PROSIT approach.

A consequence of the lack of satisfactory solutions to the multi-objective optimization analysis is that the different single-goal optimization tasks lead to conflicting geometries, thus the system must be further investigated in order to extract the “geometrical contradictions” a subclass of TRIZ physical contradiction proposed in [26].

Besides, the analysis and solution of contradictions according to the PROSIT project was still demanded to the designer, just providing a set of guidelines to overcome the conflicts according to the specific operational conditions of the technical system, as described in [7].

2.4 Embodiment design automation through topological hybridization of partial solutions

Assuming the PROSIT framework as a reference logic, the authors have developed an original algorithm which approaches the geometrical contradictions emerging from the comparison of different mono-objective optimizations through a hybridization process. More in details, the hybridization is applied to optimized density distributions obtained by means of traditional topological optimization systems by assigning just one design requirement to the objective function. Then, the hybridization, namely DAeMON (hybriDizAtion of Mono Objective optimizatioNs), is obtained through a TRIZ-inspired manipulation of the topologies to be combined, as summarized in this section.

The minimal contradiction involves two alternative density distributions arising from two topological optimizations of the same technical system (TS) where different boundary conditions are applied, as schematically represented in figure 2.4: the symbols “+” and “-“ mean that the behavior of the TS under the i-th Boundary Condition improves and worsens respectively according to the goal function of the optimization problem. In other words, the diagram in figure 2.4 should be read as follows: the density distribution should assume the topology “∨” in order to improve the behavior of the TS under the Boundary Condition #1, but then it degrades the behavior under Boundary Condition #2 and should assume the topology “∧” in order to improve the behavior of the TS under the Boundary Condition #2, but then it degrades the behavior under Boundary Condition #1.

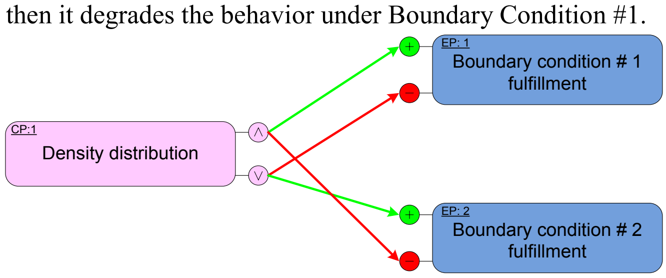

Fig. 2.4 Geometrical contradiction derived by the comparison of two topological optimizations obtained by applying alternative boundary conditions to the technical system. It is worth to notice that the density distribution is not a scalar variable, but a 3D-array representing the optimized density of each voxel of the design space.

Such a formulation clearly resembles a classical OTSM-TRIZ contradiction where the density distribution is the parameter under the control of the designer (CP) and the goal function under different Boundary Conditions constitutes the Evaluation Parameters of the Technical Contradiction [27].

More in general, a TS can experience more than two different operating conditions and consequently more than two topologically optimized density distributions can impact the same contradiction. The properties of such a "generalized contradiction" are still under investigation as well as the most effective directions to generate a satisfactory solution [28]. In this chapter only contradictions in the form represented in fig. 2.4 are taken into account.

2.4.1 Direct hybridization

Once that a geometrical contradiction in the form represented in fig. 2.4 has been identified and the mono-objective optimized topologies "∨" and "∧" have been created, the simplest way to perform hybridization is to directly combine the density distributions according to the following formula:

$$\rho(x,y,z) = \frac{K_1\rho_1(x,y,z) + K_2\rho_2(x,y,z)}{K_1 + K_2} \quad (1)$$

where:

- $\rho(x, y, z)$ is the distribution of density in the design space overcoming the geometrical contradiction;
- $\rho_i(x, y, z)$ is the distribution of density of the *i*-th mono-goal topological optimization problem;
- K_i is the weight assigned to the result of the *i*-th mono-goal optimization.

The simplest way to assign an appropriate value to the weights K_i is to refer to the potential impact of each loading condition estimated as maximum stress, maximum deformation, strain energy etc. Besides, a more efficient procedure to blend the optimized density distributions $\rho_i(x, y, z)$ has been proposed in [29] and further developed in [30], by leveraging the potential of Genetic Algorithms to identify the global optimum, but still avoiding the drawbacks GAs meet when applied to classical topological optimization.

In order to clarify the logic of the hybridization process, it is worth considering an exemplary case study taken from optimization literature, such that it is possible to make a comparison between traditional approaches and DAeMON. The problem has been taken from [24] where the multi-objective topology optimization has been performed by means of GAs and concerns the design of a steel plate having an overall dimension of 400 x 300 mm. The plate is discretized with 1200 (40x30) isoparametric plane stress finite elements, assuming an isotropic material with Young's modulus equal to 210 GPa and Poisson coefficient equal to 0.3.

As depicted in fig. 2.5 left, the plate undergoes two different point loads, a vertical force and a horizontal load, both with a magnitude of 200 N. By performing two different mono-objective optimizations according to the PROSIT logic, two conflicting geometries emerge: fig. 2.5 shows the topologies “∨” (middle) and “∧” (right) in analogy with the model of geometrical contradiction represented in fig. 2.4. The direct hybridization brings to a set of solutions which depend on their blending proportion (fig. 2.6).

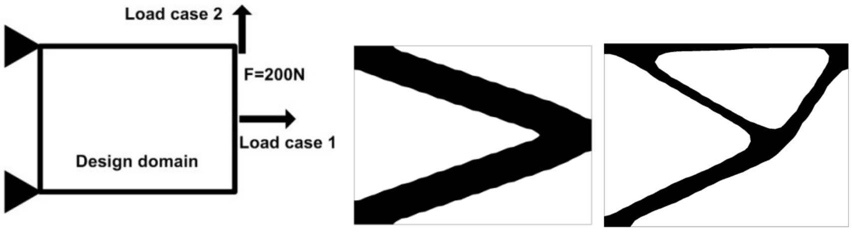

Fig. 2.5 The plate is fully constrained at the corners on the left edge and the forces are alternatively applied on the middle and the upper point of the right edge (left). Topologies obtained through mono-objective optimization under load case 1 and density threshold = 0.27 (middle) and under load case 2 and density threshold = 0.83 (right).

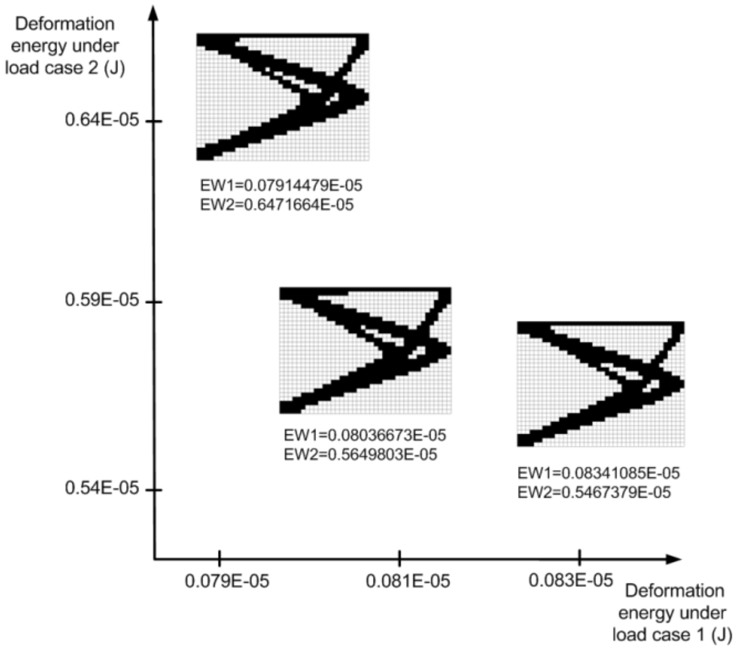

Fig. 2.6 Hybrid solutions obtained through a different blending of the mono-objective optimizations related to the two different operating conditions.

The resulting topology appears more effective (in terms of stiffness related to the overall mass) than a standard multi-objective optimization. At the same time, a comparison with the results obtained with a GA topological optimization presented in [24] reveals similar mechanical performances, but computational efforts an order of magnitude smaller. Further details on this comparison and to other similar case studies are reported in [29].

2.4.2 Rotations and translations as possible mutations for extended hybridization

Indeed, the investigation carried out by the authors about many different geometrical contradictions and related solutions [26] revealed that direct hybridization is not the only solution strategy which can be adopted to overcome a contradiction. Further relevant solution paths can be associated to TRIZ heuristics [6]:

- different orientation of a geometrical feature, i.e. a rotation of a geometrical element, or in TRIZ terms, “Another Dimension” (Inventive Principle #17);
- multiple copies obtained by a translation of a geometrical feature, as suggested from the trend of evolution Mono-Bi-Poly of homogeneous systems (Inventive Standard 3.1.1) applied to geometrical features (figure 2.5, above);
- a combination of the above, i.e. the trend Mono-Bi-Poly applied to systems with shifted characteristics (Inventive Standard 3.1.3) obtained by introducing multiple copies of a geometrical feature, each with a proper position and orientation; the simplest case is obtained by duplicating a geometrical feature by means of a mirror operation (figure 2,5, below).

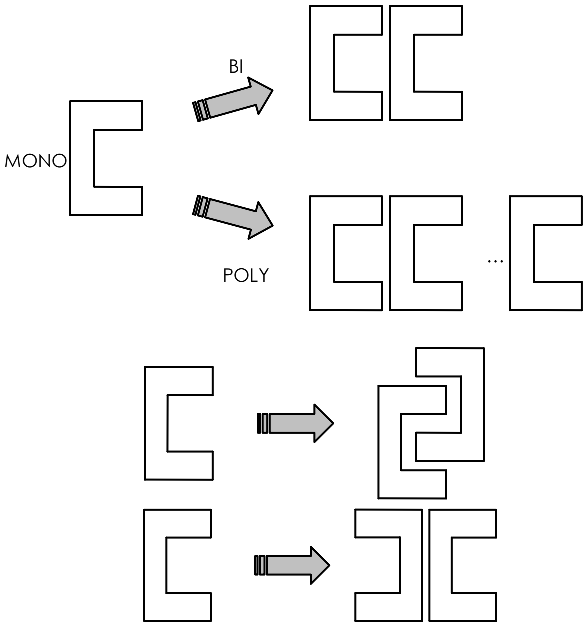

Fig. 2.5 Mono-Bi-Poly transformation applied to geometrical features (above). Exemplary bi-features obtained by a combination of rotations and translations of the original geometry (below).

A general expression capable to represent all the above solution strategies is the following:

$$\rho(x,y,z) = \frac{\sum_{i=1}^{N}\sum_{j=1}^{Mi} K_{ij}\rho_i\left(\left[ROT\right]_{ij}(x,y,z)^T + (x_0,y_0,z_0)_{ij}^T\right)}{\sum_{i=1}^{N}\sum_{j=1}^{Mi} K_{ij}} \qquad (2)$$

where

- N is the overall number of conflicting mono-goal optimizations (two if a classical TRIZ contradiction model is adopted, as represented in fig. 2.4);
- M_i is the number of "copies" of the *i*-th solution (step of a mono-bi-poly trend);
- K_{ij} is the weight assigned to the *j*-th copy of the *i*-th distribution of density;
- $[ROT]_{ij}$ is a general expression coming from Linear Algebra, describing a matrix 3 X 3 that contains Direction Cosines related to the angles between the coordinate axes of the initial and the rotated system, thus, in such context, this term represents the rotation applied to the *j*-th copy of the *i*-th distribution of density,
- $(x0, y0, z0)_{ij}$ is the translation applied to the *j*-th copy of the *i*-th distribution of density.

The appropriate values for M_i, K_{ij}, $[ROT]_{ij}$ and $(x_0, y_0, z_0)_{ij}$ are still under investigation; nevertheless, a typical combination for axial-symmetric density distribution is: Mi = 1; Kij = 1; $[ROT]_{11}$ = identity matrix (no rotations); $[ROT]_{21}$ is a rotation around the axis of the system, the angle being calculated as half the periodicity of the geometrical feature; $(x0, y0, z0)_{i1}$ = null vector (no translations).

An exemplary application of hybridization of rotated topologies refers to the redesign of a motor-scooter wheel [31]. The test case has been inspired by a real case study developed during a collaboration of the authors with the Italian motorbike producer Piaggio. The goal of the project was the design of a plastic wheel for light moto-scooters mainly aimed at costs reduction, of course without compromising safety and mechanical performances.

The traditional approach used in Piaggio to assess the conformity of a wheel to requirements consists in three different experimental tests:

1. deformation energy under high radial loads/displacements (simulating an impact against an obstacle);
2. fatigue strength under rotary bending loads (simulating the operating conditions such as curves);
3. fatigue strength under alternate torsional loads (simulating the accelerations and decelerations).

These tests have been adopted as reference criteria for topology design optimization, under the constraint of manufacturability through injection molding and the goals of minimizing mass and maximizing the stiffness distribution on the rim wheel. The optimization problem has been set up as follows:

- Objective Function: maximize wheel stiffness;
- Constraints: several upper limits for the mass of the wheel; manufacturing constraints for injection molding process;
- Loading conditions: radial and tangential loads applied on the rim of the wheel

Rim profile and hub have been defined as non-design areas since they are functional surfaces. The optimization task led to several topologies having different number of spokes (fig. 2.6). Their compliance to the design criteria above described has been checked through virtual simulations.

Results revealed that three and six spokes wheels widely satisfy the deformation energy test only when the radial load is applied on the areas of the rim directly supported by a spoke while, when the radial load is applied among them, the proof fails. The other topologies never satisfied the deformation energy criterion while all meet fatigue strength requirements (2, 3).

A deeper investigation of the radial stiffness distribution along the wheel rim has been performed for each optimized geometry (fig. 2.7). As supported also by intuition, when the number of spokes rises, the stiffness of the rim on spokes decreases, while it increases among the spokes.

According to these results a contradiction appears: a smaller number of spokes provides the highest radial stiffness in the areas of the rim directly supported by the spokes, but the deformation between two spokes is maximum. A bigger number of spokes allows to obtain a more uniform stiffness distribution along the rim but with low overall values. This technical contradiction can be modeled as shown in fig. 2.8.

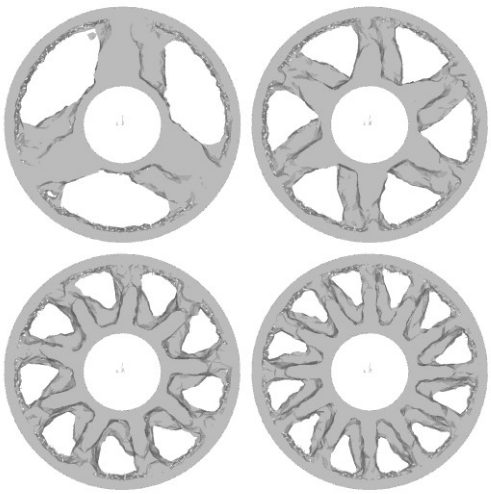

Figure 2.6 Output topologies obtained by topological optimizations: boundary conditions (loads and constraints), optimization constraint (overall mass), optimization objective and density threshold are the same for all four instances. Only the number of the pattern repetition is clearly different.

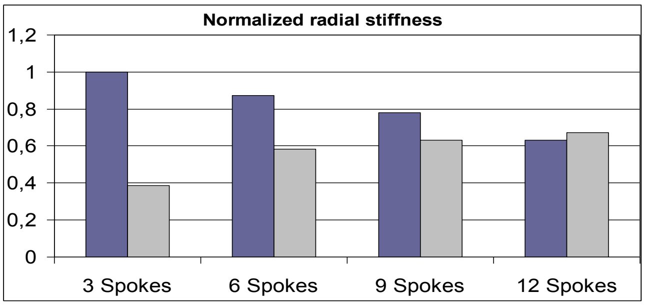

Figure 2.7 Normalized radial stiffness distribution evaluated on the wheel rim for different topologies: radial force applied on the spokes (dark) and in the middle between two adjacent spokes (light).

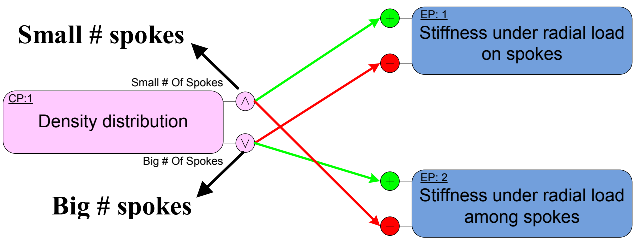

Figure 2.8 Model of the technical contradiction: EP1 is the stiffness on spokes, EP2 is the stiffness among spokes.

Taking into account these considerations, "three spokes" and "nine spokes" geometries have been selected to produce an improved "manipulated" topology through formula (2). The goal is the definition of a new topology, not identified by standard optimization systems, with a higher mechanical performance.

Taking into account the functional surfaces, the hub axis is assumed as reference to apply the transformation. The rotation is defined as a half of the angular periodicity of the nine spokes wheel, thus 20°: such a value provides the minimum overlap between the original distributions of density. Figure 2.9 shows the profile of the original distribution of densities (3 and 9 spokes wheels) and the result of the manipulation; as a result of the density combination, a "Y" shaped spoke is suggested. It is worth to notice that such a topology is definitely different from any result provided by the optimization systems.

A preliminary design of a Y-shape spoke wheel has been developed in order to compare its radial stiffness with the mechanical performance of the original geometries. Figure 2.10 summarizes the results of such a comparison.

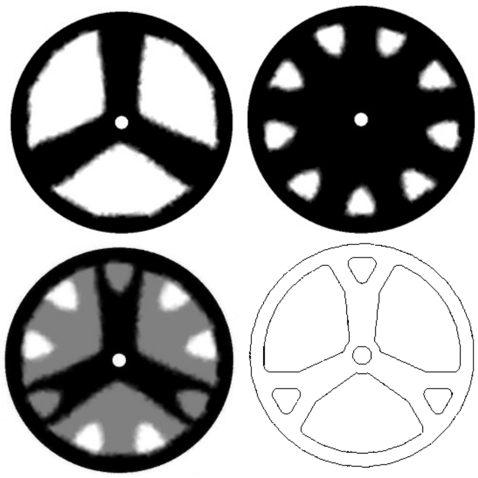

Figure 2.9 Above: conflicting distributions of density according to the contradiction modeled in figure 8 (same overall mass). Below: density distribution automatically obtained by the application of formula (2) to the conflicting pair (left) and exemplary interpreted geometry (right). The darkness of the images is directly proportional to the optimized density.

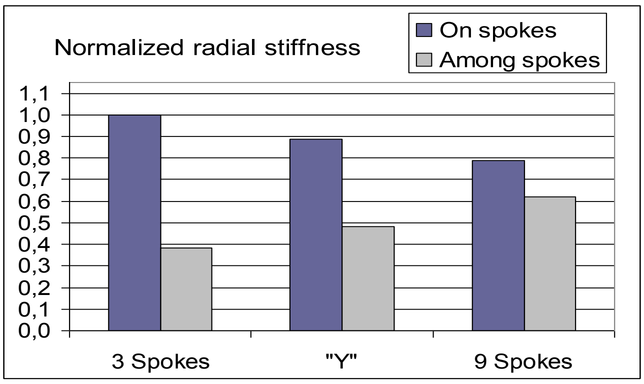

Figure 2.10 Comparison of radial stiffness distribution among “three spokes”, “Y” and “nine spokes” wheels. “Y” has an improved stiffness among spokes with respect “three spokes”. The behavior is similar to the “nine spokes” wheel but with an improved stiffness on spoke. “Y” is 20% lighter than the other configurations.

The analysis revealed that the suggested topology is 20% lighter than both the “three spokes” and “nine spokes” configurations. The “Y” version gives also an improvement of the rim radial stiffness among spokes.

Even if the stiffness evaluated on spokes worsens with respect to the “three spokes” wheel, “Y” configuration satisfies the deformation energy design criterion.

2.5 Trends of Computer-Aided Design: discussion and conclusions

Among the trends which characterize the evolution of Computer-Aided tools supporting product development, a relevant aspect is the extension of the domain of application described in section 2.2 and depicted in fig. 2.1. Indeed, the engagement of this trend can be seen as a transition from task-oriented applications to process-oriented systems: the former CAE tools were able to speed-up and sometimes automate several engineering tasks, but the integration was limited to product data exchange formats. Then, PLM systems emerged as a “strategic business approach that applies a consistent set of business solutions in support of the collaborative creation, management, dissemination, and use of product definition information across the extended enterprise from concept to end of life - integrating people, processes, business systems and information” [32].

As observed above, current PLM systems are effectively integrated just with CAD-CAE applications, but their efficiency is still poor for the preliminary design phases. In order to extend the domain of application of PLM system, a necessary transition is to introduce a modeling approach capable of representing a product at different detail levels, from the functional requirements of the earliest stages of conceptual design, to the constructive details of the manufacturing stage.

The present chapter summarizes the contribution of the authors towards the definition of a model capable to represent a mechanical part since the intermediate stage of embodiment design. In fact, the density distributions generated by topological optimizations of mono-objective tasks can be seen as elementary customized feature for the definition of the geometry of a certain mechanical part during the embodiment stage, when its functional role must be translated into a geometry to be manufactured and coupled with other subsystems.

It is worth to highlight some characteristics of these customized modeling features:

- as mentioned in section 2.2, the result of a topological optimization is a distribution of density so that each cell of the design space assumes a fuzzy value between 0 and 1, which in turns means that boundaries are not rigid as it happens also with classical free-form modeling features; in facts, a density distribution can produce both topological and shape variations while, apart few exceptions, parametric modifications of a free-form surface produce just shape variations;
- compared with free-form surfaces where a shape variation is obtained by moving many control nodes, the output of a topological optimization produces different specific geometries by editing just one parameter, i.e. the threshold value of the density discriminating between void and filled space;
- these customized modeling features can be combined according to a general formula (2) which embeds several TRIZ inventive principles, thus in-

heriting the potential to overcome the emerging geometrical contradictions, as exemplarily shown in section 2.4;
- it is important to note that the proposed hybridization approach usually leads to very different topologies with respect to traditional design multi-objective optimization; the resulting geometry has often better performance than the traditional one;
- the specific hybridization strategy can be governed by means of GAs, thus inheriting their capability to search for a global optimum, but at the same time avoiding the unaffordable computational demand of the application of GAs to topological optimization;
- compared with GAs, the DAeMON approach is also intrinsically robust against the definition of non manifold and/or non manufacturable geometries.

The adoption of topological optimization as a bridging element between the generation of a concept and the development of a detailed solution has also further advantages.

In fact, topological optimization just requires to define the design space and the functional surfaces of the part to be designed. These surfaces, can therefore be linked to the function delivered by the part itself, thus creating a connection between the abstract product representation of the conceptual design stage with the geometrical details of the following phases. Moreover, this vision fits also with the trend towards the knowledge integration into CAD systems already approached by Knowledge Based Engineering (KBE) systems to automate configuration tasks of modular products [33].

With the aim of further extending the applicability of the DAeMON logic to more complex design problems, as well to fuzzier problem situations which emerge in the development of innovative projects, the authors are also working to define a systematic link between the outcomes of a conceptual analysis made with OTSM-TRIZ techniques [27] and the set up of the mono-objective optimizations which constitute the starting point of the proposed methodology [34].

The long-term vision is a transition to a new generation of CAD systems which will guide the designer through a systematic analysis of the task to be accomplished until the functional architecture of the system has been defined [35]. Then, each functional component should be embodied starting from the definition of the optimal topology by means of the hybridization of the customized modeling features, i.e. density distributions, described in this chapter. According to this perspective, a further relevant direction of investigation is the definition of a link between a density-based representation of geometry and the classical feature-based approach, still more convenient for the following manufacturing stages.

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