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Computer-Aided Conceptual Design
Through TRIZ-based Manipulation of Topological Optimizations

G. Cascini[1], U. Cugini[1], F. S. Frillici[2], F. Rotini[2]
[1] Dip. di Meccanica, Politecnico di Milano, Italy
[2] Dip. di Meccanica e Tecnologie Ind.li, Università di Firenze, Italy
gaetano.cascini@polimi.it, umberto.cugini@polimi.it, francescosaverio.frillici@unifi.it, federico.rotini@unifi.it

Abstract

In a recent project the authors proposed the adoption of Optimization Systems [1] as a bridging element between Computer-Aided Innovation (CAI) and PLM to identify geometrical contradictions [2], a particular case of the TRIZ physical contradiction [3].

A further development of the research has revealed that the solutions obtained from several topological optimizations can be considered as elementary customized modeling features for a specific design task. The topology overcoming the arising geometrical contradiction can be obtained through a manipulation of the density distributions constituting the conflicting pair. Already two strategies of density combination have been identified as capable to solve geometrical contradictions.

Keywords:

Computer-Aided Innovation, Computer-Aided Conceptual Design, Embodiment Design, TRIZ

1 INTRODUCTION

Computer-Aided Innovation (CAI) is an emerging discipline within the environment of Computer-based systems and applications for Product Development. Despite CAI still requires a precise identification of its scientific foundation and the main directions of research, it receives a growing attention both from academia and industry as the class of software systems supporting any activity from the fuzzy front-end of product development to the following phases of detailed design.

Among the main issues to be approached by researchers in the field of CAI, a proper attention should be dedicated to: (i) the poor interoperability between computer tools actually adopted in innovation related activities, due to the lack of formalized procedures and means to accomplish conceptual design tasks [4]; (ii) the limited usability of CAD systems for conceptual design. In facts, the generation of a geometry capable of delivering a certain function is not supported by actual CAD systems, mainly conceived as a means for parametric variations of design details [5]. At the same time, also modern sketch-based 3D modeling systems still present several key problems limiting their usability [6].

In this context the authors have addressed the goal of improving the interoperability of Computer-Aided design systems by an original integration of TRIZ-based software tools with Optimization and PLM systems through the PROSIT project (www.kaemart.it/prosit) [4]. A reference book for TRIZ (Russian acronym for Theory of Inventive Problem Solving) is [3].

The promising results obtained so far have triggered the idea to adopt the results of a topological optimization as a customized modeling feature to be adopted in the embodiment design phase, i.e. when the abstract functional architecture defined in the conceptual design phase, is molded into a system to be produced.

The next section presents some open research problems from the related art and summarizes the results of the PROSIT project relevant for the present activity. Then the paper proposes an original TRIZ-based approach to combine the results of different topological optimizations in order to generate a new geometry with improved performances and characteristics compared with classical multi-objective optimizations. The fourth section reports some exemplary applications of the proposed approach to clarify its practical implementation and to discuss its expected benefits.

2 RELATED ART

2.1 Conceptual design and CAD systems

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 [7, 8].

In fact, commercial CAD systems let the users carry out successfully tasks related to the detailed design stage, but not enough efforts have been dedicated to the conceptual design phase, especially activities such as function synthesis, concept generation and exploration.

Preliminary attempts to provide conceptual design capabilities to CAD systems are in progress: in [5] shape and topological variations of a 3D model are proposed as a means to generate an optimal geometry through the application of genetic algorithms. 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.

2.2 Topological Optimization systems

Topology Optimization is a technique that determines the optimal material distribution within a given design space, by modifying the apparent material density defined as design variable. The design domain is subdivided into finite elements and the optimization algorithm alters the material distribution within the design space at each iteration, according to the objective and constraints defined by the user. The surfaces defined as “functional” by the user, are preserved from the optimization process and considered as “frozen” areas by the algorithm.

Thus, designing through Topology Optimization technique means translating a design task into a mathematical problem with the following basic entities:

- An *Objective Function,* i.e. a combination of *Evaluation Parameters*, adopted as a reference metric to assess the degree of satisfaction of the design requirements;

- A set of *Design Variables*, i.e. *material density variables* by which the design domain is parameterized; they constitute the *Control Parameters* of the system affecting the Evaluation Parameter.

- A set of *External Inputs* and *Constraints* representing the operating conditions and 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. Sliding planes and preferred draw directions may be imposed for molded, tooled and stamped parts as well as minimum or maximum size of the structural elements (i.e. ribs, wall thicknesses, etc.).

The optimization algorithm finds the material density distribution within the given design domain which minimizes, maximizes, or, in general, “improves” the objective function, i.e. the Evaluation Parameters while satisfying the Constraints.

Topology Optimization is widely used to support the design of lightweight and stiffened components, a survey of methods is presented in [9, 10]. During the last years they have been integrated in several CAE tools such as: HyperWorks [11], TOSCA [12], Nastran [13], ANSYS [14] and others.

Although Topology Optimization was born with the aim to support design tasks related to the structural fields, it has been recently applied to address design problems also in other fields such as: fluid dynamics, heat transfer and non linear structure behavior. Several works are available in literature, examples are provided in [15-17].

However, since the design process has multidisciplinary characteristics, improving one performance of a system may result in degrading another. This kind of conflicts cannot be solved using Design Optimization since these techniques are able to focus the design task only to one specific performance to be improved. More precisely, Design Optimization tools allow to manage multiple goals just by defining complex objective functions where a weight must be assigned to each specific goal [18]. 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.

The integration among Topology Optimization technique and CAD tools is another very important open issue that should be addressed in order to enhance interoperability. As stated so far, Topology Optimization uses a material density distribution within a given design domain to represent a geometry: this paradigm cannot be directly translated into the feature-based representation used in CAD tools.

2.3 The PROSIT project

By means of the PROSIT project, the authors addressed the integration of Computer-Aided Innovation systems, Optimization systems and PLM/EKM tools as a means to improve the innovation resources and the efficiency of a product development cycle. The rationale of the research was the lack of formalized and validated procedures allowing the systematic introduction and integration of these tools in the design process.

A relevant aspect of the results achieved by the PROSIT project is the integration of apparently incompatible tools, thanks to the new role and way of usage of the Optimization Systems.

The starting point is that in the design process designers have to address three subsequent interconnected tasks:

- correct problem stating (precisely formulate the right question);

- define the correct-optimal architectural-morphological answer;

- finalize the best solution taking into account the technical/engineering constraints.

In order to perform these tasks, designers have at their disposal different dedicated approaches and tools. The goal of PROSIT project was to demonstrate that it is possible to define a coherent and integrated approach leveraging on available theories, methods and tools as illustrated in figure 1 [2].

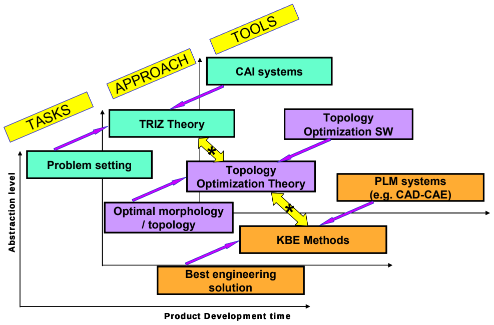

Figure 1: Methods and tools to support the tasks of a product development process.

Innovation and optimization are usually conceived as conflicting activities. Besides, topology and shape generation capabilities of modern design optimization technologies can be adopted as a means to speed-up the embodiment of innovative concepts, but also as a way to support the designer in the analysis of conflicting requirements for an easier implementation of TRIZ instruments for conceptual design. In facts: (i) defining a single multi-goal optimization problem leads to a compromise solution; (ii) besides, defining N complementary mono-goal optimization problems, each with specific boundary conditions, leads to N different solutions; (iii) these solutions can be conflicting and this is the key to find contradictions.

In [1] it was proposed a classification of these contradictions mostly related to the geometrical differences between the results of the mono-goal optimization tasks and to the nature of the conflicting design parameters:

- Size Contradictions: a dimensional parameter of the Technical System (TS) should be big and should be small according to two or more different mono-goal optimization tasks. Three different sub-classes can be defined: 1D, 2D, 3D.

- Shape Contradictions: an element or a detail should assume different forms, e.g. sharp vs. rounded details, circular and polygonal.

- Topological Contradictions: an element or a detail should assume different topologies (material distributions, e.g. monolithic and segmented) and/or orientations (e.g. horizontal and vertical etc.).

Within the PROSIT project a set of guidelines were developed to lead the designer to the identification of the most appropriate instruments of classical TRIZ for overcoming physical contradictions and in their consequent application to the development of the final solution.

It is worth to notice that the PROSIT project didn't aim at the creation of a fully automatic system for design embodiment, because both the comprehension of the root-cause of a geometrical contradiction and, most of all, the translation of the TRIZ principles into a new set of optimization tasks, requires a creative even if systematic step, demanded to the designer.

Besides, the obtained results suggested the investigation of semi-automatic procedures to combine the outputs of the single-goal optimization tasks as a means to reduce the creative contribution of the designer, still in charge to select the most suitable directions among those proposed by the computer-based system.

3 MANIPULATION OF TOPOLOGICALLY OPTIMIZED DENSITY DISTRIBUTIONS

3.1 Topologically optimized density distributions and TRIZ contradictions

As described in the previous section, instead of accepting a compromise solution generated by a multi-goal optimization, it is preferable to determine the best geometry for each boundary condition the technical system may encounter and, if these results conflict each other, adopt a TRIZ approach to overcome the emerging contradictions.

The minimal contradiction involves two alternatives 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: 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 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.

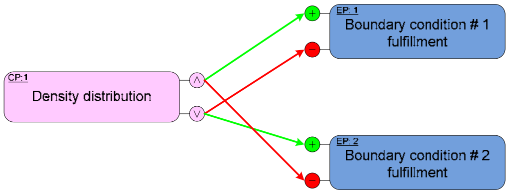

Figure 2: Geometrical contradiction derived by the comparison of two topological optimizations related to alternative boundary conditions of the technical system. The density distribution is not a scalar variable, but a 3D-array representing the optimized density of each voxel.

Such a formulation clearly resembles a classical 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 [19].

More generally 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 [20]. In this paper only contradictions in the form represented in figure 2 are taken into account.

3.2 Topologically optimized density distributions as customized 3D modeling features

A general conclusion can be drawn by the references mentioned in section 2.1: the modeling features actually adopted by CAD systems are too rigid to be compatible with the fuzziness of the preliminary steps of embodiment design. Besides, the transformation of any basic modeling elements (i.e. protrusions, revolutions etc.) into more flexible features (e.g. loft, sweep) as proposed in [5] appears computationally expensive and hard to integrate with other existing design tools.

In this paper we propose the density distributions generated by topological optimizations of mono-goal problems 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. Even if a proper discussion about this choice is postponed to the last section of the paper, 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.

Also according to the results of the PROSIT project, the embodiment design phase should start with the translation of system requirements into separate boundary conditions to build complementary mono-goal optimization problems. The solutions generated by each topological optimization can be considered as elementary modeling features to be combined as described in the following section.

3.3 TRIZ-based combinations of density distributions

When a geometrical contradiction is formulated as represented in figure 2, different strategies can be considered to define a solution capable to satisfy both the conflicting requirements.

A TRIZ expert can recognize a certain similarity between a density distribution and a team of "smart little people" [3]. From this point of view a first option to obtain the advantages of both the "values" of the density distribution is a hybridization obtained by a weighted sum of the partial values:

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

where:

- ρ(x, y, z) is the distribution of density in the design space overcoming the geometrical contradiction;
- ρ_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 investigation carried out by the authors about many different geometrical contradictions and related solutions (more details about their source can be found in [1]) revealed that typical solution paths can be associated to:

- 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 (figure 3) applied to geometrical features;
- a combination of the above, i.e. the trend Mono-Bi-Poly applied to systems with shifted characteristics obtained by introducing multiple copies of a geometrical feature, each with a proper position and orientation (figure 4); the simplest case is obtained by duplicating a geometrical feature by means of a mirror operation (figure 4, below).

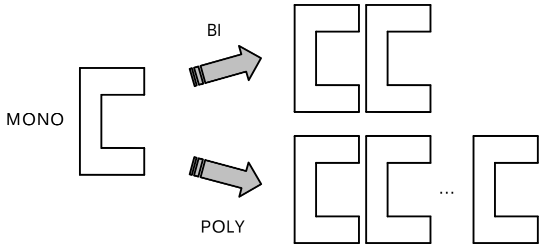

Figure 3: Mono-Bi-Poly transformation applied to geometrical features.

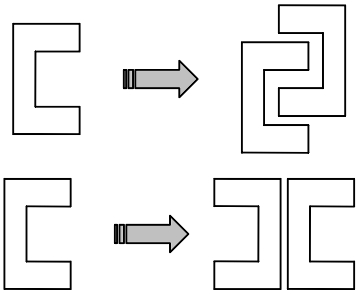

Figure 4: Exemplary bi-features obtained by a combination of rotations and translations of the original geometry.

A general expression capable to represent all the above solution strategies is the following (2):

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

where

- *N* is the overall number of conflicting mono-goal optimizations (two if a classical TRIZ contradiction model is adopted);
- 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 the rotation applied to the j-th copy of the i-th distribution of density;
- $(x_0, y_0, z_0)_{ij}$ is the translation applied to the j-th copy of the i-th distribution of density.

The authors are now collecting typical values of M_i, K_{ij}, $[ROT]_{ij}$, $(x_0, y_0, z_0)_{ij}$ from the database of examples collected in [1].

The weights K_{ij} have been added to the formula (2) to extend its adaptability to different situations, but in most cases binary values can be applied: 0 when the i-th solution doesn’t contribute to the definition of the density distribution overcoming the geometrical contradiction, 1 in the other cases. Nevertheless, while approaching hybridization strategies (e.g. the first standard combination proposed in section 3.4), fuzzy values can be assigned to the weights K_{ij}, according to the potential impact of each loading condition estimated as maximum stress, maximum deformation, strain energy etc.

3.4 Exemplary standard combinations

A typical combination for the density distributions obtained by different mono-goal optimizations is the hybridization obtained by assigning to (2) the following values:

- $M_i = 1$;
- K_{ij} = a value among 0 and 1 as a function of the relevance of each loading condition;
- $[ROT]_{ij}$ is the identity matrix (no rotations);
- $(x_0, y_0, z_0)_{ij}$ is the null vector (no translations).

It is worth to notice that the results obtained by this strategy do not necessarily coincide with the results of a multi-goal optimization performed by commercial optimization tools, as shown in section 4.2.

A second typical combination is the abovementioned mirrored geometry (fig. 4, below) obtained through:

- M_1 = any (it doesn’t impact the result due to he value assigned to the weights K_{1j});
- $M_2 = 2$ (two copies of the same density distribution);
- $K_{1j} = 0$ (only one optimized density distributions is used for generating the final geometry);
- $K_{2j} = 1$;
- $[ROT]_{21}$ is the identity matrix (no rotations);
- $[ROT]_{22}$ is a 180° rotation;
- $(x_0, y_0, z_0)_{21}$ is the null vector (no translations);
- $(x_0, y_0, z_0)_{22}$ is the minimal translation suitable to eliminate the overlap between the high density regions of the design space.

In the following section a typical combination for axialsymmetric density distribution is shown, according to the following values:

- $M_i = 1$;
- $K_{ij} = 1$;
- $[ROT]_{11}$ is the 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;
- $(x0, y0, z0)_{i1}$ is the null vector (no translations).

4 EXAMPLES AND DISCUSSIONS

With the aim to explain the approach so far described, some examples are here presented. The first case study concerns a redesign task of a motor-scooter wheel which should be manufactured using plastic material instead of aluminum alloy; the second one is related to the design of a linear guidance system that experiences two different loading conditions. The optimization tasks have been carried out by using the commercial software Optistruct embedded in the suite HyperWorks rev.7, developed by Altair Inc.

4.1 Motor-scooter wheel redesign

This test case has been inspired by a real case study developed during a collaboration of the authors with the Italian motorbike producer Piaggio [21]. 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 it 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 (figure 5).

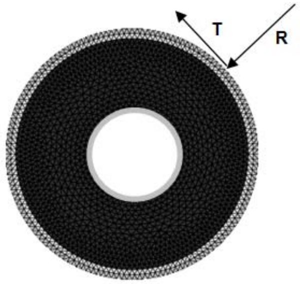

Figure 5: Design domain for Topology Optimization. The rim and the surface of the hub have been defined as functional surfaces, i.e. non design areas (light gray); dark gray represents the design space.

The optimization task led to several topologies having different number of spokes (figure 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 fulfilled fatigue strength requirements (2, 3).

A deeper investigation of the radial stiffness distribution along the wheel rim has been performed for each optimized geometry (figure 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.

Figure 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.

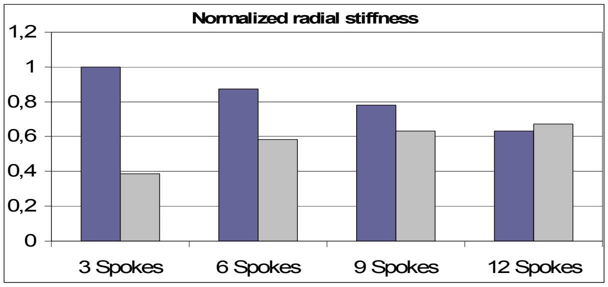

Figure 7: Normalized radial stiffness distribution evaluated on the wheel rim for different topologies: radial force applied on the spokes (dark) and in the middle between two adjacent spokes (light).

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 figure 8.

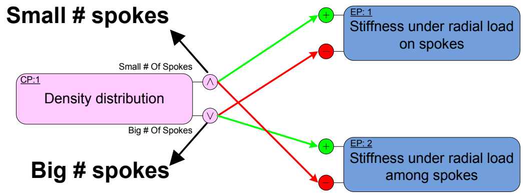

Figure 8: model of the technical contradiction: EP1 is the stiffness on spokes, EP2 is the stiffness among spokes.

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.

As described in section 3.4, axial-symmetric density distributions can be combined by a relative rotation with respect to the common reference. 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 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 concept 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 10 summarizes the results of such a comparison.

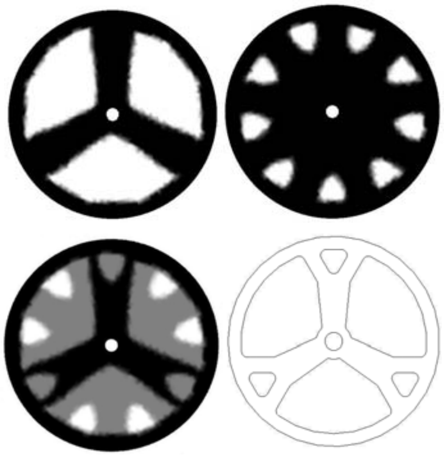

Figure 9: Above: conflicting distributions of density according to the contradiction modeled in figure 8 (same overall mass). Below: density distribution automatically obtained by the application of formula (2) to the conflicting pair (left) and exemplary interpreted geometry (right). The darkness of the images is directly proportional to the optimized density.

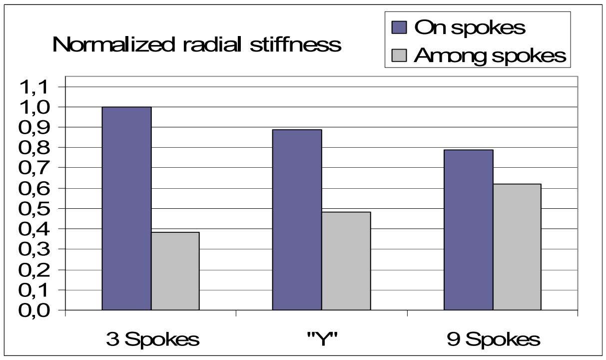

Figure 10: comparison of radial stiffness distribution among “three spokes”, “Y” and “nine spokes” wheels. “Y” has an improved stiffness among spokes with respect “three spokes”. The behavior is similar to the “nine spokes” wheel but with an improved stiffness on spoke. “Y” is 20% lighter than the other 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.

4.2 Linear guidance system design

The second case study concerns the design of a linear guidance system. New applications of such kind of component (i.e. medical machines, etc.) require units with maximum stiffness. Typically these mechanical parts experience different load cases and boundary conditions during their service life. The linear guidance system here considered is typically subjected to two load cases, as shown in figure 11: an orthogonal load and a lateral load acting on the surface of the guidance.

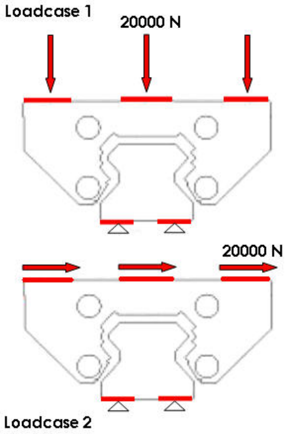

Figure 11: Exemplary cross-section of the linear guidance and applied loads [22].

As a consequence, two different mono-objective optimizations must be performed in order to obtain the customized modeling features of the system, each corresponding to a specific loading condition.

The objective for both the optimizations tasks is maximizing the stiffness of the structure evaluated as reciprocal function of the total deformation energy. A mass 16.5 kg/m has been considered as optimization constraint. Figure 12 shows the topologies emerging from these load cases.

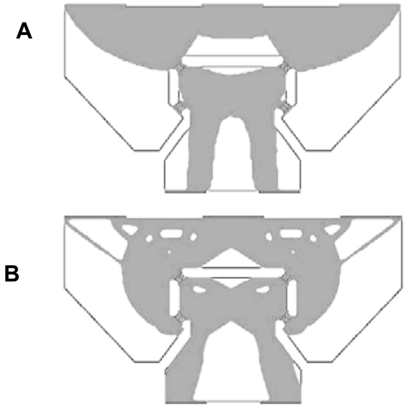

Figure 12: Topologically optimized density distribution of a linear guidance corresponding to the load cases 1 (A) and 2 (B) of figure 11.

According to these results a geometrical contradiction arises: in facts, the best density distribution for load case 1 has several topological differences with the optimized geometry for load case 2.

The geometrical contradiction can be modeled as shown in figure 13, where topology called “A” is related to the geometry shown in figure 12-A, while topology called “B” is presented in figure 13-B. The Evaluation Parameters are constituted by the total deformation energy in load cases 1 and 2.

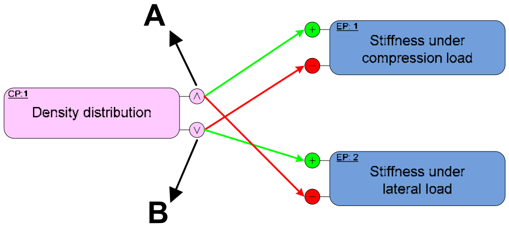

Figure 13: Geometrical contradiction: “A” is topology coming from optimization under load case 1, “B” is topology resulting from optimization under load case 2.

Due to the lack of a rotational symmetry and the constraints acting on the functional surfaces, in this case a hybridization as proposed by formula (1) is the favorite approach to generate a new topology partially overcoming the contradiction represented in figure 13. In such a case weights have been assigned in order to take into account that load case 2 involves a deformation energy greater than load case 1. Thus, density distribution “B” has been weighted correspondingly more than the density distribution “A”. This approach led to the result shown in figure 14. In order to satisfy the mass constraint of 16.5 kg/m, a density threshold of 0.85 has been considered.

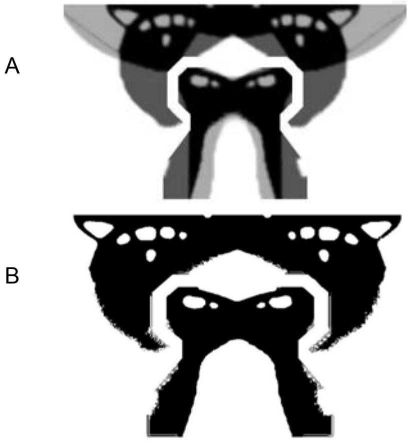

Figure 14: Above (A): hybrid solution obtained through the application of formula (1) to topologies “A” and “B” of figure 12. Below (B): resulting topology after applying a threshold equal to 0.85 to the density distribution in order to have a total mass of 16.5 kg/m.

With the aim to assess the benefits provided by the hybrid solution, a benchmark has been performed with respect to a solution obtained through traditional multi-objective design optimization, of course keeping the same mass constraint. The following objective function has been considered for this task:

$$C = w_1 C_1 + w_2 C_2 \qquad (3)$$

where:

- C is the deformation energy of the multi-goal optimization, to be minimized
- C_i is the deformation energy related to the i-th load case;
- w_i is the weight assigned to the i-th loadcase.

The weights assumed in (3) have been applied also to perform the hybridization task, according to (1).

The optimized topology is shown in figure 15.

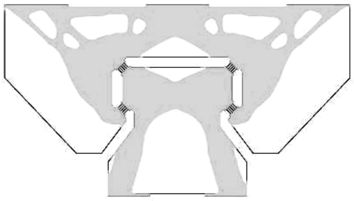

Figure 15: Topology resulting from multi-objective design optimization according to the objective function (3) under a mass constraint equal to the hybrid topology (figure12B).

According to these results an evaluation of the deformation energy for both hybrid and multi-objective solutions has been carried out taking into account each load case. The analysis brings the results shown in table 1.

	Total Strain Energy (mJ)	
	Loadcase 1	Loadcase 2
Multiobjective	6,63E-01	6,04E-01
Hybrid	4,65E-01	4,96E-01
Δ%	-30	-18

Table 1: Comparison of deformation energy among multi-objective solution and hybrid solution. The last one is more effective, thus partially overcomes the geometrical contradiction represented in figure 13.

It is worth to notice that the suggested hybridization is surprisingly much better than the solution obtained through the traditional approach based on multi-objective optimization. In fact, the hybrid solution is somehow similar to the topology presented in figure 12B and quite different from the multi-objective optimized geometry shown in figure 15. Design optimization always leads to the best compromise density distribution since it is driven by an objective function constituted by a combination of Evaluation Parameters related to different conflicting conditions. In this case, the optimization algorithm has presumably reached a local minimum. Besides, hybridization considers solutions coming from mono-objective optimizations each having the task to improve a single Evaluation Parameter. This allows to preserve and extract the useful features of each solution and trim the redundant ones.

5 DISCUSSION AND CONCLUSIONS

The papers presents the preliminary results of a research aimed at the definition of a new approach to Computer-Aided Conceptual Design: topological optimization systems are adopted as a means to identify geometrical contradictions, i.e. conflicting density distributions responding to different boundary conditions. Those topologically optimized density distributions can be assumed as customized modeling features to generate a geometry capable to overcome the geometrical contradiction.

In order to combine these customized modeling features, a general expression able to reproduce at a geometrical level several TRIZ inventive principles has been proposed. Among the different strategies to manipulate conflicting density distributions identified so far, two exemplary combinations have been detailed: hybridization and integration of axial-symmetrical topologies obtained through a rotation around their axis.

According to the results so far described, the proposed approach leads to very different topologies with respect to the traditional design optimization; the resulting geometry has often better performance than an equivalent multi-objective optimization.

At present the methodology is under validation by several other case studies in order to determine further combination criteria according to the specific resources, boundary conditions, etc.

Another important issue is the definition of criteria to perform the interpretation of the manipulated density distribution. As shown in the previous section, the raw solution coming from the automatic manipulation of the conflicting density distributions, presents different levels of density, thus generating sometimes fuzzy borders to be defined by means of a threshold. Indeed, such information can be kept while designing composite parts as well as directions for the introduction of stiffening like ribs, etc.

A further development of the present research is the extension of the procedure to topological optimizations not limited to the structural characteristics of the system. From this point of view, the expected trend in the field is the introduction in the market of multidisciplinary optimization systems with increased capabilities.

REFERENCES

[1] Cascini G., Rissone P., Rotini F., 2007, From design optimization systems to geometrical contradictions, Proceedings of the 7th ETRIA TRIZ Future Conference, Frankfurt, Germany, 6-8 November 2007.

[2] Cugini U., Cascini G., Muzzupappa M., Nigrelli V., 2008, Integrated Computer-Aided Innovation: the PROSIT approach, submitted for publications to the Special Issue on Computer-Aided Innovation of the Journal of Computers in Industry.

[3] Altshuller, G.S.: “Creativity as an Exact Science: The Theory of the Solution of Inventive Problems”. Gordon and Breach Science Publishers, ISBN 0-677-21230-5, 1984 (original publication in Russian - 1979).

[4] Cugini U., Cascini G., Ugolotti M., 2007, Enhancing interoperability in the design process – The PROSIT approach, Proceedings of the 2nd IFIP Working Conference on Computer Aided Innovation, Brighton (MI), USA, 8-9 October, 2007, published on “Trends in Computer-Aided Innovation”, Springer, ISBN 978-0-387-75455-0, pp. 189-200.

[5] N. Leon-Rovira, J. M. Cueva, D. Silva, J. Gutierrez, 2007, Automatic shape and topology variations in 3D CAD environments for genetic optimization, International Journal of Computer Applications in Technology, Vol. 30, No.1/2, pp. 59 – 68.

[6] L. Burak Kara, K. Shimada, S. D. Marmalefsky, 2007, An evaluation of user experience with a sketch-based 3D modeling system, Computers & Graphics, Volume 31, Issue 4, August 2007, Pages 580-597.

[7] S. F. Qin, R. Harrison, A. A. West, I. N. Jordanov, D. K. Wright, 2003, A framework of web-based conceptual design, Computers in Industry, Volume 50, Issue 2, Pages 153 - 164.

[8] M. Tovey, J. Owen, 2000, Sketching and direct CAD modeling in Automotive Design, Design Studies, Volume 21, Issue 6, Pages 569-588.

[9] K. Saitou, K. Izui, S. Nishiwaki, P. Papalambros, 2005, A survey of structural optimization in mechanical product development in Journal of Computing and Information Science in Engineering, Volume 5, Issue 3, Pages 214-226.

[10] R. Kicinger, T. Arciszewski, K. De Jong K, 2005 Evolutionary computation and structural design: a survey of the state-of-the-art, in Computers and Structures, Volume 83, Pages 1943–1978.

[11] ALTAIR: www.altair.com

[12] FE-DESIGN: www.fe-design.de

[13] MSC SOFTWARE: www.mscsoftware.com

[14] ANSYS Inc.: www.ansys.com

[15] W. Hutabarat, G. T. Parks, J. P. Jarret, W. N. Dawes, P. J. Clarkson, 2008, Aerodynamic Topology Optimisation Using an Implicit Representation and a Multiobjective Genetic Algorithm. In Artificial Evolution, Lectures Notes in Computer Science, Volume 4926, Pages 148-159, Springer Berlin / Heidelberg.

[16] T.E. Bruns, 2007, Topology optimization of convection-dominated, steady-state heat transfer problems. International Journal of Heat and Mass Transfer, Volume 50, Issues 15-16, Pages 2859-2873.

[17] T.E. Bruns, D.A. Tortorelli, 2001, Topology optimization of non-linear elastic structures and compliant mechanisms. Computer Methods in Applied Mechanics and Engineering, Volume 190, Issues 26-27, Pages 3443-3459.

[18] D. Spath, W. Neithardt, C. Bangert, 2002, Optimized design with topology and shape optimization. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, Volume 216, Issue 8, Pages 1187-1191.

[19] N.Khomenko, R. De Guio, L. Lelait, I.Kaikov, 2007, A Framework for OTSM-TRIZ Based Computer Support to be used in Complex Problem Management, International Journal of Computer Application in Technology, Volume 30, Issue 1/2.

[20] T. Eltzer, R. De Guio, 2007, Constraint based modelling as a mean to link dialectical thinking and corporate data. Application to the Design of Experiments, Proceedings of the 2nd IFIP Working Conference on Computer Aided Innovation, Brighton (MI), USA, 8-9 October, 2007, published on “Trends in Computer-Aided Innovation”, Springer, ISBN 978-0-387-75455-0, pp. 145-156.

[21] G. Cascini , P. Rissone, 2004, Plastics design: integrating TRIZ creativity and semantic knowledge portals. In Journal of Engineering Design, Special Issue: “Knowledge Engineering & Management Issues in Engineering Design Practices”, Volume 15, Issue 4, Pages 405-424.

[22] J. Sauter, R. Meske, 2001, Industrial applications of topology and shape optimization with TOSCA and ABAQUS. In Proceeding of ABAQUS World Users‘ Conference, 29th May – 1st June, Maastricht (Nederland).