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From design optimization systems to geometrical contradictions

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Abstract

Within the framework of the Research Project PROSIT [1] aimed at the development of an integrated product design platform capable to link Computer-Aided Innovation (CAI) with PLM/EKM systems, the authors have approached the analysis of the contradictions emerging during the design embodiment phase. In this case, since the functional architecture of the product is already fixed, design conflicts arise due to contradictory geometrical requirements. Design Optimization systems can play a relevant role for the identification of these "geometrical contradictions", even if with modified criteria of usage.
The present paper first describes how Design Optimization can be adopted as a means to link CAI and PLM/EKM systems; then a detailed analysis of geometrical contradictions is reported together with the criteria proposed for their categorization. Finally, the discussion is focused on the adoption of the proposed classification of geometrical contradictions as a pointer to the most suitable inventive principles and geometrical effects to overcome the design conflicts.

Keywords: Systematic design; TRIZ; Computer-Aided innovation; Topological optimization; Shape optimization;

1. Introduction

Within the goal of improving the efficiency of product development technologies, several research activities are dedicated to the combination of methods and tools for improving specific design tasks. Nevertheless, still a poor integration exists between the conceptual design and the detailed design phases at least in terms of Computer-Aided systems.

Pointing to a vertical integration of the whole design cycle, a small consortium of Italian Universities is analyzing the opportunity to use the geometry definition capabilities of Design Optimization as a means for linking Computer-Aided Innovation (CAI) tools with Product Lifecycle Management (PLM) systems: detailed references are provided in the website of the PROSIT project [1].

According to the diagram of Fig. 1, the PROSIT project aims at bridging three different classes of product development methods and systems, CAI and Optimization systems from one side, Optimization systems and PLM/EKM tools to the other.

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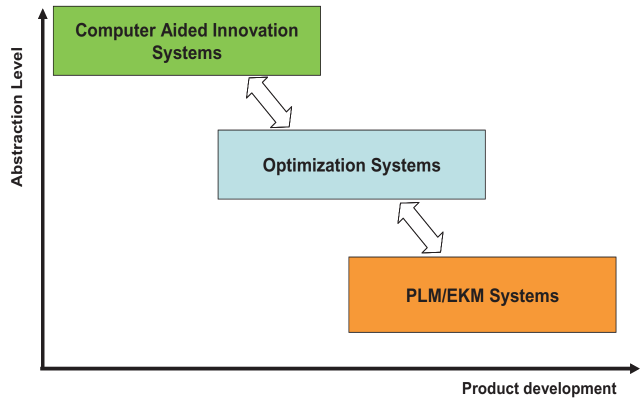

Figure 1: Integration of methods and tools for product development according to the PROSIT approach.

The main idea of the methodology developed in the frame of the project to link CAI and Optimization systems is the adoption of the latter tools not just to generate optimized solutions, but also as a means for design analysis, capable to outline critical aspects of a mechanical component in terms of conflicting design requirements or parameters.

The logic behind CAI systems is mostly related to the TRIZ theory, i.e. to the refusal of trade-offs; thus, they are apparently in conflict with the logic of optimization, seen as minimization of negative issues within a given set of constraints. Nevertheless, as explained in [2, 3], optimization systems can be used in a novel mode, such that they can play a relevant role in the identification of contradictions.

More specifically, the traditional approach to optimization involves the application of a complete system of constraints and loads to the geometry for describing all the design requirements.

It is worth to notice that this "optimal" i.e. "best compromise" solution is unnecessarily satisfying. It's often useful, before moving towards the detailed definition of the product architecture, to re-discuss already made assumptions, in order to obtain a solution which better satisfies general system objectives. On the basis of these considerations, the authors have proposed in [2] to perform a set of mono-objective optimization tasks in order to put in evidence conflicts among geometrical elements of the system under analysis.

The rationale behind the adoption of Optimization Systems as a means for design analysis is the following:

- defining a single multi-goal optimization problem leads to a compromise solution;
- besides, defining N complementary mono-goal 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.

According to this statement, the PROSIT design flow is structured as depicted in Fig. 2. The process starts with the definition of a set of single-goal optimization tasks, each representing a specific operating condition and/or a given design requirement for the technical system (TS) under development. If each output solution satisfies the design objectives and they mutually fit each other, the process doesn't require any iteration and a detailed CAD model can be produced: the definition of a bridge between Optimization and PLM systems is a further goal of the PROSIT project, but it won't be described in the present paper.

Besides, if the solution of at least one of the optimization tasks doesn't fit the design requirements and/or the optimization tasks lead to conflicting geometries, the system must be further investigated in order to extract the geometrical contradictions.

Here the application of TRIZ principles has been studied for overcoming those geometrical contradiction: the present work describes the criteria adopted to classify the geometrical contradictions and to define a pointer to the most suitable set of inventive principles/geometrical effects.

Closing the loop, as a result of this activity, a new set of optimization problems can be identified and can be solved making use of the optimization tools. In other words, the TRIZ principles are used to redefine the design volume, the functional surfaces and/or the optimization constraints so that the conflict between the design parameters disappears. This procedure has to be iterated until optimization process' results converge, i.e. the geometries generated by the different single-goal optimization tasks fit each other.

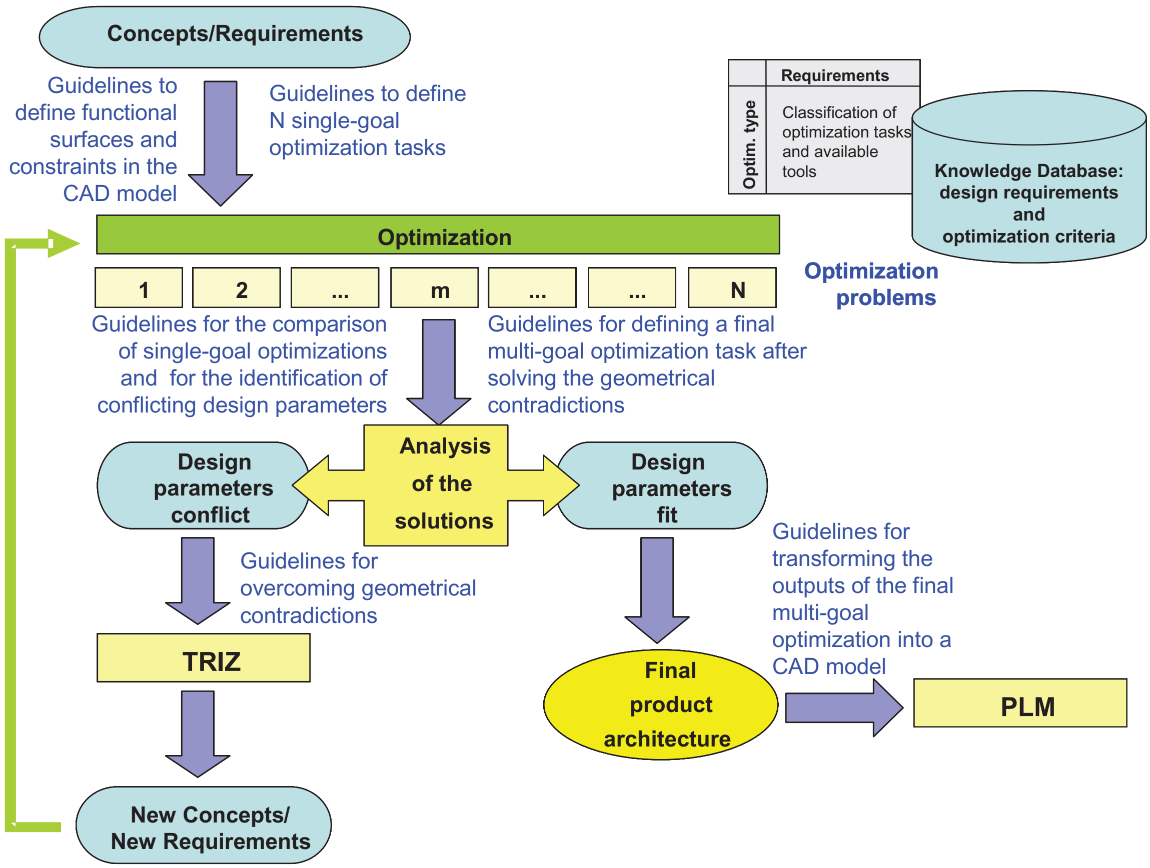

Figure 2: Design flow according to the PROSIT approach.

2. Related art

The most complete survey of the recent research studies about structural design tools covering the whole process from the generation of design concepts (design topologies and layouts), through preliminary design (design shape specification) and detailed design (sizing of structural members) is reported in [4].

Among the crucial issues related to the creative phase of the design process, the most challenging from the perspective of the creation of a Computer-Based system certainly is the capability not only to explore values of attributes (decision variables) within a given design space, but also to evolve the quantity and the quality of these attributes, i.e. when changes in the representation space occur.

According to the design flow proposed within the PROSIT project, the role of the optimization systems is to explore the design space, while the creative step is demanded to the redefinition of the design space and/or the optimization objectives and constraints made through the implementation of the TRIZ guidelines.

The purpose of the authors is thus to define a set of criteria to classify the contradictions emerging from a number of explorations of the design space and to extract the most effective strategies for a rearrangement of the design features. It is worth to remind that the proposed procedure is fully dedicated to the definition of the geometry of the technical system to be designed, when its functional architecture has been already fixed.

Within the TRIZ literature the most comprehensive and acknowledged studies about Geometrical Effects (GE) have been published by Vikentiev [5, 6].

Somehow it can be stated that "GE start where physical and chemical effects end", or more precisely, unlike chemical effects, which enable to obtain some substances from others by the absorption or isolation of energy, and physical effects that enable to transform one form of energy into another, GE usually organize and redistribute flows of energy and substances that are already available in the system.

The collection of GE gathered by Vikentiev by means of an extensive analysis of patented solutions is structured so to provide a sort of functional index: in other words the pointer to the most suitable GE is addressed by the function requested by the designer: e.g. control/regulate the volume, localize/intensify the effect, receive/contain a support etc.

While the collected GE constitute a comprehensive information fund for the present research, the pointer doesn't satisfy the need to define a set of guidelines to overcome the geometrical contradictions emerging from the comparison of several optimization outputs.

Therefore, the authors have established a novel set of classification criteria to associate GE and relevant Inventive Principles to geometrical contradictions.

3. Method for classifying geometrical contradictions

The research has been carried out by analyzing a hundred inventive solutions based on a geometrical evolution of the system, extracted from the authors' experience (a dozen of real case studies) and a higher number of patents identified through geometry-related terms.

Such a set of selected geometrical solutions has been analyzed in terms of type of contradiction, maturity level of the product, Su-Field model representing its functional interactions, GE and Inventive Principles associated to the inventive step from the previous existing geometry to the invented solution.

The inductive approach has been complemented with a deduction-based reasoning in order to organize the emerging correlations, as detailed below.

3.1. Time/Condition based classification

As described in the first section of the present paper, the mono-goal optimization tasks can bring to contradictory results. These optimization tasks can encompass several situations:

- The TS during its working cycle is submitted to different loading conditions: these different operating conditions can be mutually exclusive or totally independent from each other. E.g. a connecting rod for combustion engines alternatively supports traction and compression loads: the geometries emerging by the optimizations operated separately are represented in figure 3. Besides glass canopies in a cold country can be charged by wind loads and/or snow etc.

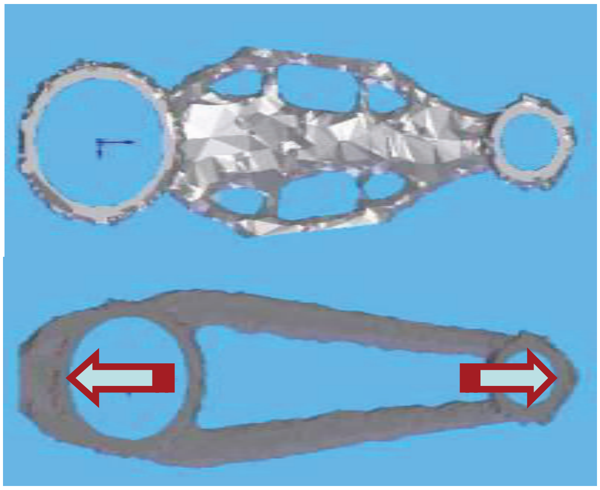

Figure 3: Optimized topologies of a connecting rod emerging from mono-goal analyses: compression (above) and traction (below) loads.

- The TS must satisfy certain geometrical constraints for manufacturing issues, but its geometrical optimization under operating conditions doesn't lead to satisfactory results if the manufacturing constraints are kept. A practical example is constituted by the design of a plastic wheel for motor-scooters [7]: in order to support high radial loads, like those resulting by the impact against a rigid obstacle, the optimization suggests the design of a hollow wheel with a double web supporting the side of the rim (figure 4, right). Besides, the application of a draw direction for manufacturability leads to a single central web that drastically impacts its mechanical properties (Fig. 4, left).

- The disposal and/or recycling phase may imply geometrical constraints which compromise the optimization under the operating conditions. For example a plastic bottle for drinking water or the container of a liquid soap must be collapsible when the product is exhausted, but such a requirement applied within the optimization of the bottle stiffness brings to unsatisfactory results.

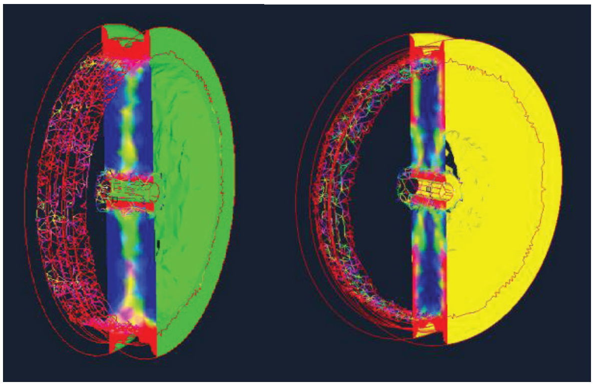

Figure 4: The Topological Optimization of a plastic wheel for light motor-scooters with and without manufacturing constraints leads to a geometrical contradiction: the radial stiffness under radial loads is not sufficient if the manufacturing constraints are respected (left), while the mechanical performance fits the requirements by removing such a constraint (right).

As a general rule the geometrical contradictions can be related to different life phases of the TS, or in "TRIZ terms" to the columns of the System Operator; in the present work the following major stages have been taken into account for classifying contradictions:

- manufacturing VS operation
- operation VS operation
- operation VS end of life.

A more detailed list of life phases and sub-phases adopted for classification is shown in figure 5.

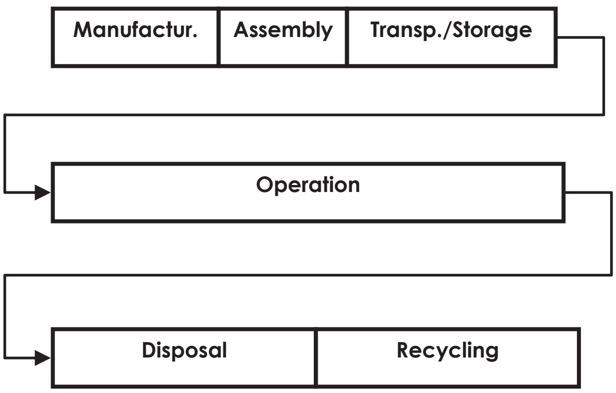

Figure 5: Life phases of a TS taken into account for contradictions classification.

Indeed, such a type of contradiction arises, for example, when conflicting technical solutions are suggested by different Design For X rules: the typical approach consists in choosing a compromise solution between those different design parameters.

3.2. Classification based on geometrical differences

By comparing two “contradictory” geometries emerging from different optimization tasks, the following types of diversities can be observed:

- Size Contradictions: a dimensional parameter of the 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 (figure 6).

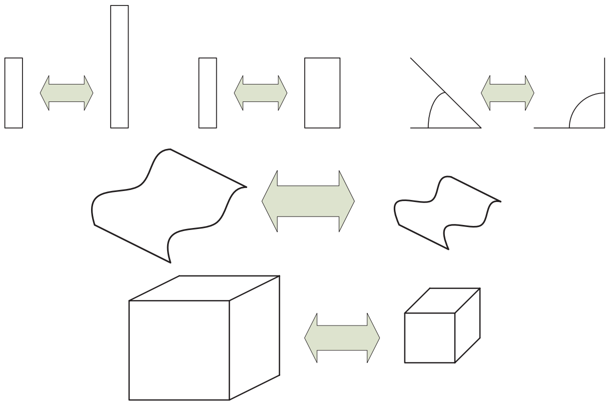

Figure 6: Exemplary representations of Size Contradictions: 1D (above), 2D (middle), 3d (below).

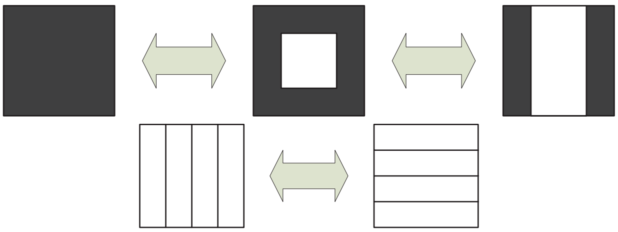

Figure 7: Exemplary topological contradictions: different material distributions (above) or different position/orientation (below).

- Shape Contradictions: an element or a detail should assume different forms (e.g. sharp and rounded, circular and polygonal etc).
- 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. – figure 7).

3.3. Functional based classification

Whatever the TS is, its elementary functional model comprehends a Supply, a Transmission, a Tool and a Control according to the flow of energy/ substance/information characterizing the way the TS performs its function (thick continuous line in figure 8). As mentioned in section 2, GE restructure the flows of energy and substances already available in the TS, thus it is worth to consider such a functional representation as a means to classify geometrical contradictions with the aim of defining a pointer to the most suitable GE.

Taking into account a typical Geometrical Optimization task, it can be stated that the “functional surfaces” (i.e. the interfaces of the TS with the environment not modified by the optimization process) correspond to the portion of supply, tool, control interacting with the supersystem. In other words, Optimization Systems typically modify only the transmission and its interaction with the tool, the supply and the control (dashed line in figure 8).

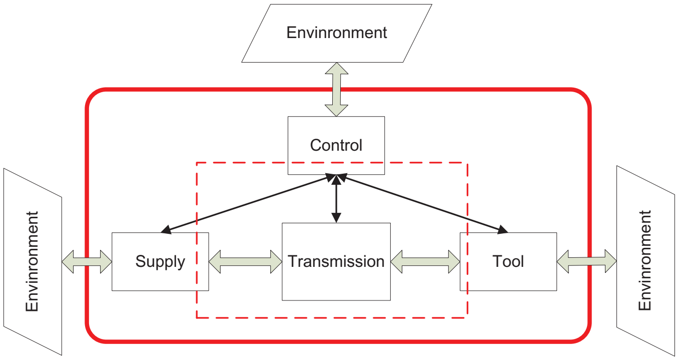

Figure 8: Elementary functional model of a TS: the thick continuous line delimits the TS itself, the dashed line represents the portion of TS subjected to geometrical optimization in a typical Geometrical Optimization task.

It is proposed to check whether the geometrical elements where the conflict resides, belong to the Transmission, its interactions or to the other elements, thus involving also the functional surfaces of the TS.

In both the examples of figures 3 and 4 (the connecting rod for combustion engines and the motor-scooter wheel) the geometrical contradiction is topological and involves just the transmission of the TS. A different situation can be encountered for example while designing a disc brake: it is required a stiff connection to the wheel hub in order to transmit the braking torque, but a soft link would be preferable in order to compensate thermal deformations and to reduce the consequent stresses. In this case the geometrical contradiction is not related to the transmission, but involves the tool of the TS, i.e. the functional surface acting on the hub of the wheel.

On a wider perspective, the analysis of the whole set of examples adopted to build and validate the proposed classification revealed that both the "positive" and the "negative machine" must be taken into account when the TS under design is responsible of an useful (desired) and a harmful (undesired) interaction. More specifically, in these cases two different elementary functional models should be built, one describing the desired flow of substance/energy/information, the other representing the harmful process. It is worth to notice that not necessarily the positive and the negative machines coincide. Let's consider a CPU cooler: the heat sink dissipates heat, but at the same time stops the air flow, thus requiring a bigger fan and a higher power consumption. Here the geometrical contradiction is related to the size of the heat sink: it should be high to improve the heat exchange surface and should be small in order to reduce the pressure drop applied to the air flow (figure 9).

From the functional point of view, the surface of the heat sink constitutes the supply of the positive machine (the cooling stream flows from here to the tool, i.e. the base that absorbs heat from the CPU), and at the same time it is the tool of the negative machine (since it directly acts on the air flow creating a counter force).

In conclusions, it is suggested to identify the functional role of the conflicting geometrical features both for the positive and the negative machine.

Figure 9: A CPU cooler is characterized by a 1d-size contradiction (long/short heat sink).

3.4. From geometrical contradictions to solving principles/effects

The combined classification integrating the criteria described in sections 3.1-3.3 constitutes a structured reference to build a reliable pointer to the most suitable inventive principles and GE to overcome geometrical contradictions. In facts, the whole set of about a hundred solutions which overcome geometrical contradictions, used to carry on the present study, has been analyzed according to the schema represented in figure 10 that combines together all the criteria described above. Such an information fund is (still) not rich enough to extract statistically reliable correlations between types of contradictions and solution principles. Nevertheless, the first correlation analyses performed so far revealed coherent results. In other words according to this study, geometrical contradictions belonging to the same class (Time/Condition - Functional Portion - Geometrical Differences) have been solved by a limited number of inventive principles/GE.

The authors are not claiming that such a classification is a novel 3D contradiction matrix, since it is well known that Altshuller himself abandoned the development of this kind of instrument after a much more extensive investigation, due to its poor reliability. However, probably due to the limited domain of modification allowed during the embodiment phase, the extracted correlations sound promising.

Moreover the nature of the classification itself allows to apply a complementary deduction-based reasoning. A few exemplary deductions will be reported here after, while a more comprehensive description is demanded to a next publication. The format of these associations geometrical contradiction-solution path has been defined with the perspective of generating a Knowledge-driven user interface within the PROSIT software platform:

- If the geometrical contradiction involves both the operation and another stage of the product life (e.g. manufacturing, transportation etc) it is clear that separation in time strategies are conceptually feasible. In order to have a TS assuming different configurations/behaviors in different stages of its life, a typical solution principle is, for example, dynamization.
- If the geometrical contradiction appears due to alternative requirements and/or loading conditions during the operation phase, a separation in time strategy means that the TS may assume different configurations. It is clear that such a solution is limited by the speed of the processes involved: in the example of the connecting rod a separation in space would imply a modification of the central link coordinated with the rotation speed of the engine; besides, it is much easier to tune the behavior of the TS according to slower processes (day/night, summer/winter etc).
- A geometrical contradiction belonging to the operation phase, such that the process is too fast to perform a separation in time or submitted to independent loading conditions (e.g. wind and/or snow) should be approached with a separation in space strategy (segmentation, another dimension, asymmetry, local quality, nested dolls…). Since in the embodiment phase it is preferable to avoid major changes in the adjacent components, a separation in space is the best option if the geometrical contradiction is located in the functional transmission of the TS, i.e. the portion of the design space where the Optimization software tool is allowed to introduce modifications. In this case, according to the dataset analyzed in this study, the type of geometrical contradiction (size-shape-topological) assumes a relevant role to point to a suitable solution path.
- If the geometrical contradiction is located outside the transmission, i.e. it involves the functional surfaces of the design volume, it is requested a change in the way the main useful function is delivered. It is worth to remind that this study is dedicated to the embodiment phase of product development, therefore the physical/chemical principle adopted to perform the main useful function shouldn't be changed. Besides, it can be changed the way the functional flow of material/energy/information is introduced in the TS or is applied by the TS to the target of the action. Here a direct link to Vikentiev's pointer to GE [5] can be created: in facts, if the contradiction resides in the tool of the TS, the function associated to the tool should be adopted to enter in the Vikentiev's pointer to GE, while if the contradiction is related to the supply of the TS, it means that the TS is the receiver of a function to be assumed as the pointer input.
- In any case, if the geometrical contradiction covers two or more functional portions of the TS, i.e. two or more among tool, transmission, supply and control, a separation in space strategy can be applied, by assigning different values in different regions to the conflicting geometrical features/parameters.

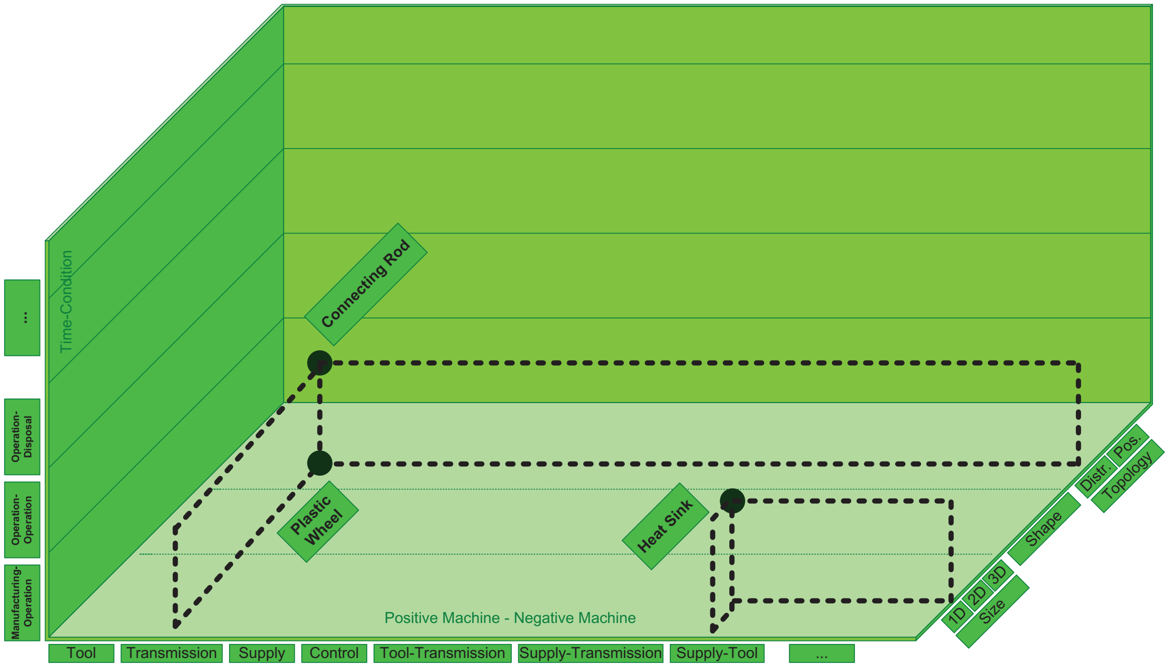

Figure 10: Combined classification of geometrical contradictions according to the criteria defined in section 3. The exemplary diagram represents the geometrical contradiction emerged from the analysis of a connecting rod for combustion engine (figure 3): Topological Contradiction (Material Distribution) of the Transmission of the TS within its Operating Phase.

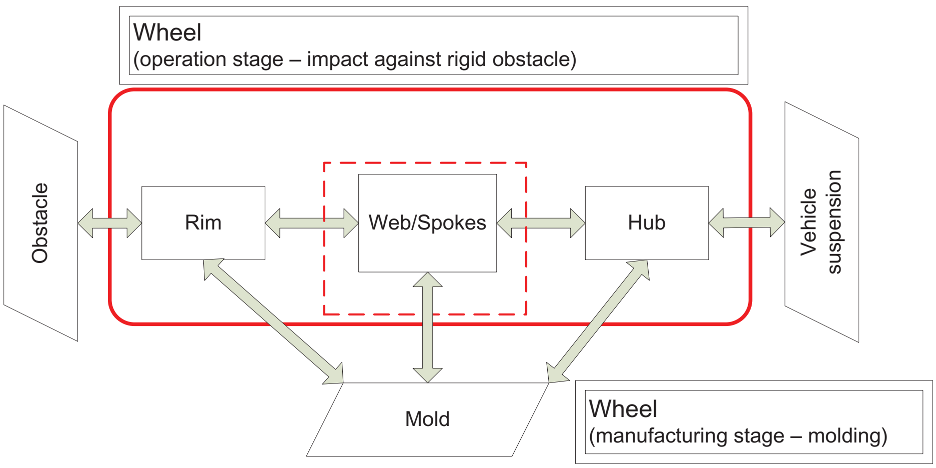

Figure 11: Elementary functional model of a wheel for motor-scooters during an impact against a rigid obstacle and during the manufacturing phase. The dashed line highlight the region where the geometrical contradiction occurs: the solution principle will be applied in this region of the design volume.

- When the geometrical contradiction involves two different stages of life of the TS, for example manufacturing and operation, it is still useful to consider the operational space where the contradiction occur as an element of a supply-transmission-tool chain, in order to focus the attention on the portion of the design volume where a modification of the representation space is required. In the example of the plastic wheel for motor-scooters (figure 4), the conflict area is limited to the web, i.e. the transmission during the operational stage. In case of impact against an obstacle, the harmful mechanical energy (to be dissipated as much a s possible) flows from the rim, through the wheel and in order to have a higher capability to absorb energy a double web directly supporting the sides of the rim is suggested by the Optimization system

Besides, such a solution interferes with the manufacturing stage, since it is not possible to produce a hollow wheel through injection molding. In this case the mold is the tool of another technical system (the injection molding apparatus) interacting with the wheel as shown in figure 11. Since the geometrical contradiction involves just the transmission of the TS, introducing a separation in time means defining two configurations of the wheel: one optimized for the functional behavior of the wheel, the other to allow a proper interaction with the mold during the manufacturing stage. Indeed a solution is to build a "segmented" wheel, so that the double web (transmission) can be built in two parts and then assembled to provide a proper mechanical stiffness to the wheel [7].

4. Discussion and conclusions

The present work, still in progress, attempts to develop a set of guidelines to be integrated in a CAD platform in order to support the designer in the analysis of the conflicting geometrical features of the TS under development and to provide systematic directions for the implementation of a solution that overcomes latent "geometrical contradictions".

In order to fulfill this goal the authors have carried out the analysis of a number of inventive solutions based on geometrical changes of a system. On the base of this analysis three complementary criteria for categorizing geometrical contradictions have been defined. These criteria were selected since according to the analyzed case studies, they provide coherent connections between classes of geometrical contradictions and relevant inventive principles and geometrical effects. It is worth to mention that during this research activities, further classification criteria have been attempted, but with less encouraging results. More specifically, the same set of geometrical contradictions-solutions has been classified also in terms of:

- Maturity level of the product: the hypothesis was that different solution strategies should be applied to products characterized by different stages of evolution. Despite the nature of the problems to be solved changes with the evolution of a TS (moving from performance improvements to complementary characteristics like reliability, efficiency and finally cost), it was not possible to identify relevant correlations between the maturity level of a product (even combined with the other classification criteria) and the solution paths. An explanation to this missing correlation can be found in the intrinsic nature of a geometrical modification of a system: since the energy transformations are kept and the impact is limited to a reorganization of functional flows, it can be stated that geometrical contradictions and geometrical effects are more relevant in the latter stages of evolution, while physical and chemical effects play a significant role in the first two stages. As a partial confirmation of this statement, the biggest majority (more than 75%) of the analyzed examples were related to "mature" or even "obsolescent" products.
- Su-Field model: a further classification criterion investigated during this activity is based on the form of the Su-Field model representing the Geometrical Contradiction. For example the contradiction emerged from the analysis of a CPU cooler (figure 9) can be represented as depicted in figure 12. According to the directions (inward/outward the TS) and the nature of the functional interactions (useful/harmful, sufficient/insufficient etc), it would be possible to distinguish the geometrical contradictions in different classes. On the base of the analyses performed so far, there are no evident correlations between these classes and the solution models.

Besides, the proposed classification criteria revealed promising connections with the models of solution (both inventive principles and geometrical effects).

Moreover, due to their intrinsic nature, some logical deductions can be associated to those classes, thus providing a logical structure to the pointer from a model of geometrical contradictions to the related models of solution.

The authors are still validating with further case studies the proposed classification. At the same time they are developing an algorithm to associate relevant inventive principles and GE to models of geometrical contradictions: according to the purposes of the PROSIT project, this algorithm will be integrated in a software suite and by means of questions and suggestions will guide the designer through the analysis of the conflicting geometrical features to the redefinition of the optimization tasks.

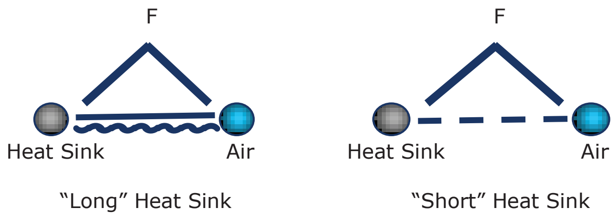

Figure 12: Su-Field model of the geometrical contradiction related to a CPU cooler (figure 9).

Acknowledgments

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List of acronyms

CAD – Computer-Aided Design
CAI – Computer-Aided Innovation
EKM – Enterprise Knowledge Management
GE – Geometrical Effects
PLM – Product Lifecycle Management
TS – Technical System

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