EMBODIMENT DESIGN THROUGH THE INTEGRATION OF OTSM-TRIZ SITUATION ANALYSIS WITH TOPOLOGICAL HYBRIDIZATION OF PARTIAL SOLUTIONS

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ABSTRACT

Many design approaches have been developed to support the tasks involved in the Conceptual and Embodiment design phases, but their nature has led to very different paradigms. The translation of the system concept into its structure still represents a critical task, since the models adopted for conceptual design are not directly compatible with those involved in the embodiment stage. Enhancing the interoperability of these models is therefore a key issue to improve the overall efficiency of the Product Design Cycle. According to this objective, in this paper an investigation is presented, aimed at testing the integration between OTSM-TRIZ approach to concept development and DAeMON, which is an original technique for multi-objective optimization developed by the authors. The functionality of the proposed model has been verified through its application to a case study concerning the redesign of a dot printer component. The results demonstrate the potential of the integrated paradigm in guiding the designer from the identification of the right problem to solve, to the embodiment of the solution. Furthermore, such experience allowed a preliminary investigation of a set of rules for developing a new framework for innovative embodiment tasks.

Keywords: Topological Optimization, Hybridization, Embodiment Design, OTSM-TRIZ.

1. INTRODUCTION

The Conceptual and Embodiment design phases play a relevant role in determining the success of a product and many researchers have spent a lot of efforts in systematizing and strengthening the tasks involved in such phases. Several authors in the engineering design literature, as in [1], describe the conceptual stage as the phase where the designer focuses his action on the definition of the system structure at the functional level (F), trying to identify all the needed functions that the technical system should perform in order to obtain the desired goal, i.e. the accomplishment of the user needs. Once a first function structure has been defined, the task of the designer moves towards the search of possible physical principles viable to implement the identified functions, allowing the attainment of the desired effect. The translation of functions into effects brings to the behavioral model of the system (B). Eventually, during the Embodiment phase, the designer focuses its activity on establishing a form of the system capable to produce the expected behavior. Thus, elements having the proper shape/structure (S) are defined aimed at implementing the physical principles in accordance with the required levels of the system performances.
Pahl and Beitz [2] prescribed precise tasks and solution paths for the Conceptual and Embodiment phases. Through the Conceptual design, the elaboration of a solution principle is performed by identifying the essential problems to be solved using an abstraction path, establishing function structures, searching for appropriate working principles and combining these into a working structure; during the Embodiment design, the identified solution principle or concept of the technical system, is developed in accordance with technical and economic criteria and in the light of further information, to the point where subsequent detail design can lead directly to production.
During the years, many approaches have been suggested to support the specific tasks involved in such phases, in order to improve the novelty of the technical solutions and to speed up their lead time. Nevertheless, the different nature of these activities, has led to the definition of methods and tools extremely different from each others. From the one hand, conceptual design activities require techniques to guide the cognitive processes through the problem abstraction and to enhance, exploit

and systematize the designer creativity. On the other hand, the representation of the artifacts through detailed geometrical models has been considered the main requirement for supporting the embodiment of the technical solution.
Due to the substantial differences among the techniques adopted in the different design stages, the translation of the behavioral model of the technical system into its structure, still results an insufficiently supported task. Thus, enhancing the interoperability of these models is a primary research goal for the engineering design community in order to improve the efficiency of the whole design process.
With the aim to pursue such an objective, the PROSIT project [3] proposed an original model based on the integration of Computer-Aided Innovation systems, Optimization systems and PLM/EKM tools, to integrate conceptualization and embodiment activities. The goal of PROSIT was to demonstrate that it is possible to define a coherent and integrated approach leveraging on available theories, methods and tools. In this paper the authors present an investigation of a possible way to integrate tools for the analysis of complex problems, useful to systematize the Conceptual design phase with the PROSIT paradigm. More in detail, the design of a dot printing head is analyzed since the formalization of the technical problems to solve by means of an OTSM-TRIZ approach. Then, the embodiment of its most critical part is assumed as a reference case study to investigate the opportunity of integration with the PROSIT logic.
The contents of the paper are organized as it follows: in Section 2 a brief analysis of the related art is performed with the aim to contextualize the specific objective of this work and give information about the adopted reference models. Section 3 reports the detailed description of the performed investigation and the achieved results. Section 4 is dedicated to the discussion about the proposed integration, while Section 5 reports the conclusions and further directions of study.

2. RELATED ART

In order to support the tasks involved in the Conceptual and Embodiment design phases, several models, tailored on the specific objective, have been developed during the years. Here a brief review of the literature relevant for the purposes of the paper is presented, with the aim to highlight the main mismatching features that prevent the attainment of a full interoperability.
Functional modeling is one of the fundamental paradigms of the systematic approach to engineering design [2]. It provides useful formalisms to support the translation of the goal of the system, expressed in the form of user needs, into a function structure. This result is attained through the capability of functional modeling, to guide the cognitive processes along an abstraction path, leading to a general representation of the specific problem to be solved. These models are almost useless to practically support an embodiment activity.
The synthesis of the behavioral model starting from the system functional architecture uses techniques devoted to enabling, enhancing and guiding creative processes for the identification of original conceptual solutions. A wide range of formal methods for problem analysis and idea generation, have been developed [2, 4, 5]. Among these, in the opinion of the authors, OTSM-TRIZ (Russian acronym for “General Theory of Powerful Thinking”), is one of the most suitable suite of models to manage complex non typical interdisciplinary problems [6], while TRIZ inventive solution principles together with other inventive tools [7], can be considered powerful models that provide systematic paths for the generation of original physical solutions.
Despite such techniques are efficient for managing problem complexity and for identifying the suitable solution principles by which implementing the expected system functions, they don’t give any support in defining an embodiment of such principles into a working structure of the system.
Besides, CAD/CAE systems are based on models dedicated to the detailed representation of the artifact features to support verification tasks aimed at identifying the critical functional aspects of a structure, and performing faster modifications. Due to their nature, CAD and CAE techniques do not provide any problem-solving functionality. Moreover, they don’t give any suggestion about the way to synthesize a possible embodiment of the behavioral model of the system [8].
Preliminary attempts to provide conceptual design capabilities to CAD systems are in progress: 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. Nevertheless, topological and shape variations are obtained through the modification of classical 3D modeling features, which dramatically limit the design space and impact the usability of the proposed method.

Topology Optimization [10] can be considered a first attempt to fill the gap between Conceptual and Embodiment phases. This technique is able to provide a possible structure of the technical system in the form of a material distribution within a given volume, where a fictitious material density is defined as design variable. The design space is explored by an optimization algorithm which alters the fictitious material density according to the design objectives defined by the user. The output of the process is represented by a material density distribution that suggests the geometry of the technical system. Although solving the embodiment task through an optimization approach could speed up the design process, it doesn't allow any involvement of the designer creativity, thus optimization could bring to trade-off solutions in case of design tasks characterized by conflicting requirements. Moreover Topology Optimization techniques present unsolved problems that still limit their employment [11] since they are computational expensive and have a low efficacy in finding global optimum solutions for engineering problems.

Further developments of the results achieved in the PROSIT project [3], have led to an original implementation of the proposed approach, namely DAeMON (hybriDizAtion of Mono-Objective optimizatioNs) [11]. In it, Topology Optimization is used to explore partial embodiments of the technical system by performing mono-objective optimizations aimed at improving one performance at the time. Such embodiments are defined through different material density distributions which are combined together by TRIZ-inspired manipulations. The result is a possible geometry of the technical system, merging together all the positive features of the partial embodiments identified by the mono-objective optimizations.

The proposed approach is able to deal with embodiment problems characterized by several conflicting requirements, such as those related to the definition of a geometry of the technical system. Even if it leads to the identification of original non-trade-offs solutions, in the first publications about the DAeMON still there are no suggestions dedicated to assisting the problem analysis, managing the problem complexity, identifying relevant parameters governing the system behavior and their impact on its performances. The integration in the DAeMON workflow of suitable problem analysis techniques aimed at identifying the most critical design issues could enhance interoperability and give an important contribution in filling the gap between Conceptual and Embodiment design phases.

Within this context, the present paper is specifically aimed at investigating how OTSM-TRIZ and DAeMON techniques can be complementarily used to model the complexity of a system, identify the relevant bottlenecks and synthesize solutions for problems related to system performances depending on its geometry.

3 TOWARDS AN INTEGRATED APPROACH: REFLECTIONS FROM A CASE STUDY

The authors were involved in a project at ESC Engineering, an Italian SME experienced with dot impact printing technology, aimed at defining new solutions for a printing head [12]. The case study employed to verify the benefits that could arise from the integration of OTSM-TRIZ and DAeMON approaches, concerns a small part of the printing head belonging to the dot matrix printer.

More in particular, the design task concerns a small metallic element, named "armature", that supports and pushes a single welded needle of the matrix toward the ink ribbon. At rest, the armature leans on an electromagnetic coil and on a dumper (named backstop) and it is maintained in its position by a spring and a preloaded o-ring (Figure 1). The printing action takes place when the armature is attracted by the electromagnetic coil. In a printing head there are 24 armatures disposed on a circumference, each acting on a single needle. The working frequency of each armature is about 1500 Hz.

In order to verify the effectiveness of the proposed approach, the achieved embodiments have been compared with the solutions identified by the experts of ESC Engineering.

In section 3.1 the problem situation analysis related to the armature is presented according to the OTSM-TRIZ modeling paradigm. Starting from the obtained results, the embodiment of the armature has been performed through DAeMON; section 3.2 reports the outcomes of this activity. Eventually the section 3.3 presents the achieved results.

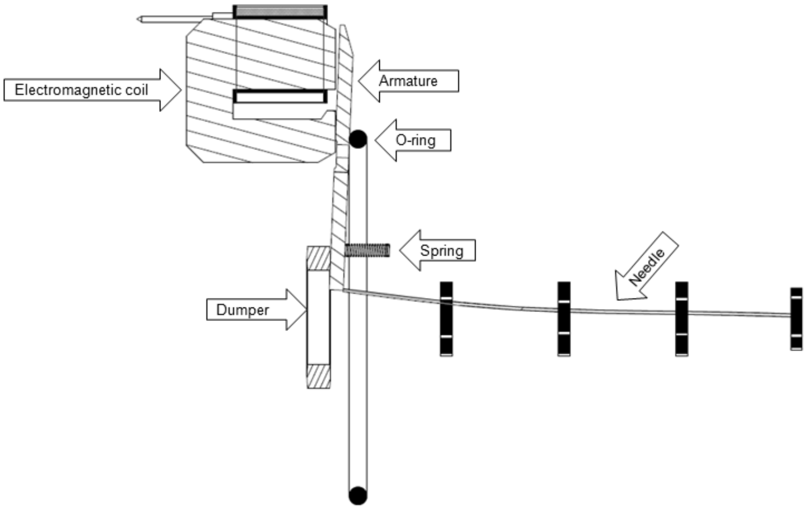

Figure 1. Cross sectional view of the armature apparatus.

3.1 PROBLEM ANALYSIS THROUGH OTSM-TRIZ

The study started from the analysis of the original armature designed by the experts, who have obtained the final embodiment without using computer aided optimization tools and without focusing the design task on any of the specific objectives related to its functionality.

In order to analyze the whole problem situation of the printing head, TRIZ experts together with domain experts, have built the Network of Problems (NoP) according to the OTSM-TRIZ rules [13]. NoP is a modeling technique that allows to analyze and to decompose an overall complex problem into several sub-problems (Pb). Solving an elementary problem, leads to a solution that cannot be considered as a global one, but only a Partial Solution (PS). When a PS is identified, very often it generates one or more new elementary problem(s). Thus the analysis and decomposition of the overall problem creates a network constituted by elementary problems and partial solutions; this network is updated after each design session in order to keep track of the outcomes and of the remaining issues to be addressed. The NoP related to the dot printer is constituted by 39 sub problems and 56 partial solutions connected by a net of 127 links.

As OTSM-TRIZ suggests, a sequence Pb-PS-Pb underlies a contradiction. In fact, since a partial solution solves an elementary problem but, at the same time, creates a new one, it means that such partial solution is needed to address the first problem, but at the same time it should be avoided to impede the emergency of the new problem. The analysis of the sequences Pb-PS-Pb brings to the identification of Evaluation Parameters (EPs) and Control Parameters (CPs) allowing the formalization of such contradictions. According to the OTSM-TRIZ contradiction model [13], an EP represents a measure of a certain requirement of the system, while CP is a design variable of the system (i.e. its mass, shape, etc.) governing or somehow impacting one or more performances. Thus, at least, one EP can be identified from each Pb box while one CP can be extracted from each PS box (Table 1).

All the contradictions summarized in the NoP can be collected in a new chart named Network of Parameters (NoPa). For the considered case study, 39 contradictions regarding all the components of the system have been identified. In order to address this quite complex problem, two different strategies could be adopted. An approach consists in prioritizing the contradictions by assigning a score to each one and starting the solution process from that having the highest relevance score [14]. The alternative approach consists in focusing the solving efforts on the problems related to a specific component of the system. Such a task requires to extract a sub net from the NoP and, consequently, a sub net from the NoPa, and to solve the contradictions related to it. As recalled above, the authors have decided to address the problems related to the armature supporting the needle, thus they adopted the second approach. For this component the NoP highlighted several technical problems, mainly impacting the following conflicting performances of the system: high noise generation, high cycle time due to a high time of flight of the needle, insufficient impact force, versatility with different types of paper, heat dissipation and needles wearing. The NoP branches collecting boxes of specific problems Pb and partial solutions PS inherent with the armature have been further analyzed. Thus, starting from these, a sub-net constituted by problems and/or partial solutions exclusively related to the topological properties of the armature have been extracted (Figure). For the sake of clarity, the topological properties are represented by all the physical characteristics of the armature that depend on its geometry and mass.

Table 1. Table of Evaluation Parameters and Control Parameters extracted from the whole Network of Problem. In the CP column the elements of the system to which each parameter is referred, have been reported as well as the two opposite values that the CP has to assume in order to satisfy the different performances (EP).

EP
Noise
noise by needle/tape impact
structural vibration
noise by needle/backstop impact
noise by gap closure
noise by impact on the core
needle wearing
backstop wearing
permanent deformation of the backstop
thermal deformation
bounds
cycle time
time of flight
starting point of needle
easy of manufacturing
jam between needle and tape
needle speed
size
number of components
assemby tolerances
impact force
versatility
gap between “armature” and core
pushing force
“armature” size
core and coil size
“armature” positioning
heat generation
heat generation
heat generation by Joule effect
safety
heat generation
heat generation by hysteresis
heat generation by Eddy currents
post assembly re-working
current rising time
heat disposal
needle driving

CP			
Element	**Parameter**	**V1**	**V2**
Roller	presence	yes	no
Paper	pressure	high	low
Tape	tension	high	low
“armature”& core	contact stiffness	high	low
silentblock	presence	yes	no
full stroke surface	hardness	high	low
needle	material	tungsten	other
backstop	material	hard	soft
backstop	temperature	high	low
backstop & other components	distance	high	low
backstop & needles	distance	high	low
spring	stiffness	high	low
permanent magnet	presence	yes	no
additional coil	presence	yes	no
electric current	spectrum	impulsive	continuos
needle	stroke	long	short
“armature”& needle	inertia	high	low
current ramp	velocity	high	low
coil	magnetic field	high	low
magnetic circuit	reluctance	high	low
spring	torque	high	low
cores	number	high	low
“armature”	reluctance	high	low
core	geometry	complex	simple
“armature”& core	distance	high	low
“armature”	number of component	high	low
“armature”	pivoting	yes	no
coil	force	high	low
“armature”+needle	mass	high	low
needle	diameter	high	low
“armature”	mass	high	low
needle	stroke	high	low
“armature”	stroke	high	low
“armature”	lever ratio	high	low
needles	layout	radial	spiral
electric current	amplitude	high	low
coil	lenght	high	low
coil	cross section	high	low
coil	tension	high	low
core &“armature”	material hysteresis	high	low
core &“armature”	typer of structure	segmented	solid
metallic plate	presence	yes	no
core	structure	segmented	solid
core	structure	solid	porous
core	structure	segmented	solid
insulating material	presence	yes	no
cover	structure	open	closed
insulating material	presence	yes	no
insulating material	presence	yes	no
cover	material	alluminium	other
coil/core & cover	distance	high	low
insulating material	presence	yes	no
cover	shape	finned	flat
needle	transmission of energy	mechanical	e.m.
micro coil	axial position	far	close
micro coil	controlled needles	multiple	single

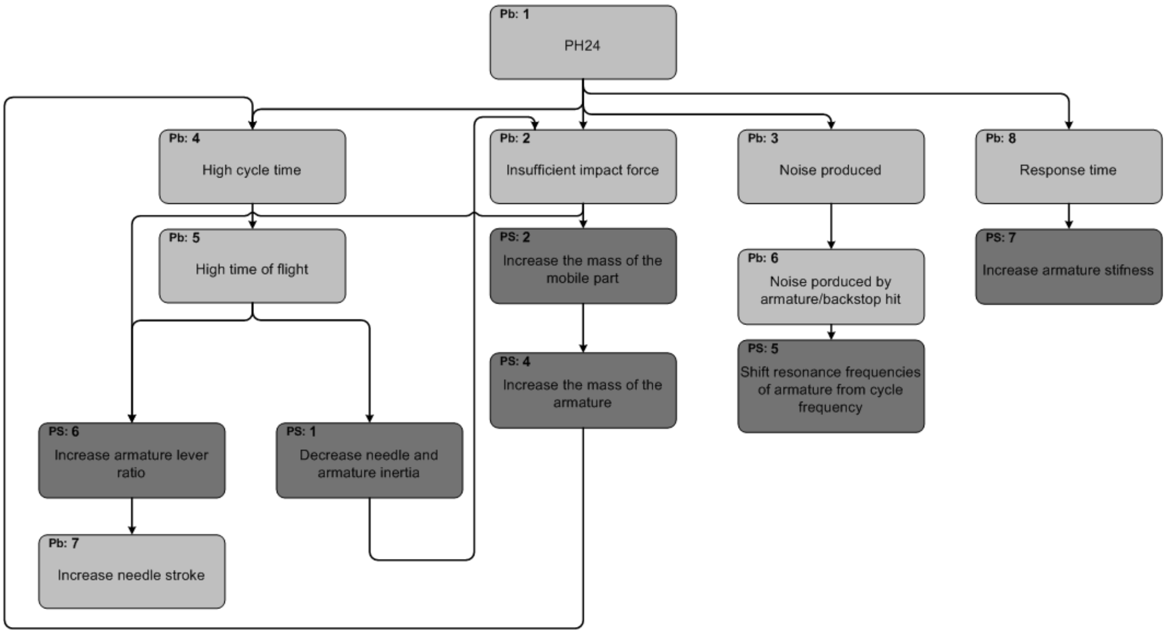

Figure 2. The sub-net regarding just geometrical parameters of the armature.The light grey boxes represent Problems (Pb), while dark grey boxes are the Partial Solutions (PS).

By following the logic suggested by OTSM-TRIZ, a contradiction can be extracted (Figure 3) from each Pb-PS-Pb sequence within the NoP portion related to the armature and, in this way, the whole Network of Parameters related to this component can be built (Figure 4). The analysis of NoPa led to the identification of three contradictions: one related to a property of the armature that depends on its geometry (i.e. the moment of inertia), the other two concerning the position of the pivot around which the armature can rotate (it does not represent a topological property since refers to a functional surface). It is worth to notice that, within the NoPa, two CPs are not involved in a contradiction (first resonance frequency and stiffness), but they give alike some useful information about the actions to be undertaken to improve the system performances related to such CPs. In particular, looking to the needs to reduce noise, the NoPa suggests keeping the first natural vibration frequency of the armature away from the working frequency, while looking to the response time, a high value of the armature stiffness can improve this performance.

Thus, the analysis of the NoPa highlights the critical bottlenecks limiting the system performances; hence the designer can decide what are the ways and actions for their removal, according to the nature of such bottlenecks. For problems not involving contradictions, such as those related to the noise or the response time, a way to reach an embodiment satisfying the goals, could be performing a topological optimization in order to define a geometry with the desired properties. Besides, design problems requiring a non standard solution, typically underlie contradictions that require the application of appropriate solving techniques, e.g. the TRIZ Inventive Standards.

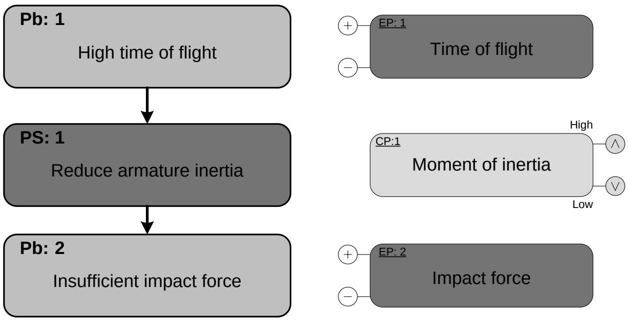

Figure 3. On the left: the Problem-PartialSolution-Problem sequence that suggests the presence of a contradiction. On the right: the Evaluation Parameters and the Control Parameter derived respectively from the problems and from the partial solution.

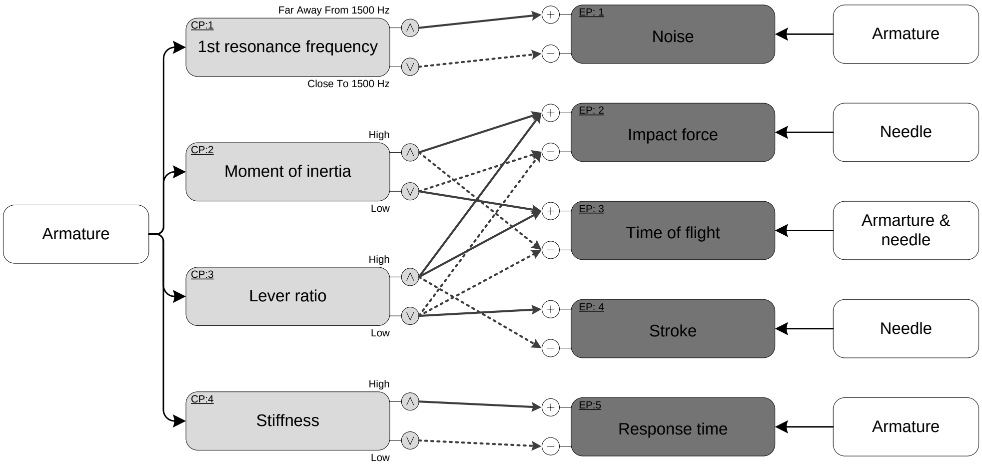

Figure 4. Exemplary excerpt from the Network of Parameters (NoPa) related to the armature.

3.2 PROBLEM SOLUTION THROUGH DAeMON

The task refers on the application of the DAeMON logic [11] in order to solve the problems highlighted by the NoPa that are related to the topological properties of the armature, and obtaining its embodiment solution.

As introduced in Section 2, if N performances of the system should be improved, DAeMON suggests to:

1. perform N mono-objectives optimizations, each one focused on the improvement of one and only one performance at time;
2. obtain N different density distributions constituting partial embodiments of the technical system;
3. combining together such partial solutions through the formula for hybridization of partial solutions which is a particular case of that extensively described in [15]:

$$\rho(x,y,z)=\frac{\sum_{i=1}^{N}K_i\rho_i(x,y,z)}{\sum_{i=1}^{N}K_i} \quad (1)$$

where:

1. $\rho(x,y,z)$ represents the density distribution related to the hybridized topology;
2. N is the overall number of mono-objective optimizations;
3. $\rho_i(x,y,z)$ represents the density distribution related to the i-th partial embodiment obtained by the i-th mono-objective optimization;
4. K_i is the weight assigned to the i-th distribution of density;

Taking into account the problem situation arisen from the NoPa, two contradictions involving the lever ratio could not be brought back to a topological problem since they are related to the position of the armature pivot, that is not a topological CP. Thus, they cannot be solved by DAeMON but require the use of classical TRIZ tools. However, for the purposes of this investigation, such circumstance does not represent a drawback since the goal of the research is to verify the benefits arisen from the integration between OTSM-TRIZ and DAeMON for solving embodiment problems when a multi-objective optimization approach brings to solutions that are not able to satisfy the design requirements.
Looking to the contradiction concerning the moment of inertia, NoPa suggests a high value of this CP in order to obtain a high impact force (EP1) but, at the same time, this implies that the time of flight (EP2) increases, and, vice versa. Thus, solving the recalled contradiction according to DAeMON, requires defining two different topologies, one having the highest and the other one having the lowest moment of inertia. In fact, the partial solution having a high moment of inertia presents a high impact force, while the partial solution having a low moment of inertia guarantees a short time of flight. Thus,

hybridizing together these two partial embodiments through (1), should bring to an overall solution owning the expected requirements in terms of impact force and time of flight.
Eventually, the NoPa does not highlight any contradiction related to the performances depending on the first natural vibration frequency and the stiffness properties of the armature. However, it gives precise searching directions to obtain the partial solutions improving both the response time and the armature noise behavior. In fact, the NoPa suggests to perform a topology optimization task having the minimization of the natural vibration frequency as objective, in order to identify the partial embodiment owning the best performance in terms of noise behavior, whereas it suggests the designer to perform an optimization task maximizing the stiffness in order to obtain the partial embodiment presenting the lower response time.
Thus, summarizing the suggestion arisen from the analysis of the NoPa, 4 mono-objective optimization tasks are needed for implementing the DAeMON hybridization approach:

- minimization of the armature moment of inertia leading to the partial embodiment with the shortest time of flight;
- maximization of the armature moment of inertia leading to the partial embodiment with the highest impact force;
- maximization of the armature stiffness bringing to the partial embodiment presenting the quickest response time;
- minimization of the armature natural vibration frequency bringing to the partial embodiment having the lowest dynamic response at the working frequency;

Some generalizations can be proposed through this experience and other similar case studies analyzed by the authors: the process of translating the problem situation analysis described by the NoPa into a set of solving tasks based on the DAeMON logic, follows some general rules which can be codified. If *n* CPs of the technical system are referred to topological properties underlying *n* contradictions, and *m* CPs of the technical system are referred to topological properties not underlying any contradiction, then:

1. the *n* CPs are used as objective of *2n* topological optimization tasks;
2. *n* topology optimizations are performed to define *n* embodiments of the system having the highest value of the CPs;
3. *n* topology optimization are performed to define *n* embodiments of the system leading to the lowest value of the CPs;
4. *m* CPs are used as objective of *m* topological optimization tasks aimed at defining *m* embodiments of the system having the best performances related to such CPs;
5. when all the partial embodiments represented by *2n+ m* density distributions are available, the formula (1) is applied in order to combine them, and, simultaneously, overcoming the contradictions caused by the *n* different topological properties highlighted by the NoPa.

3.2.1 APPLICATION OF DAeMON

According to the above described rules, a set of mono-objective optimizations has been defined to generate the seeds for the following hybridization task. The employed Finite Element model is shown in Figure 5, as well as the design volume, the boundary conditions and the loads used for the mono-objective topology optimizations. The volumes depicted with light gray, are the non design areas representing functional parts or surfaces of the armature which cannot be modified due to external constraints. The volumes depicted with dark gray are the design areas in which the optimization algorithm performs the material distribution, trying to achieve the specific objectives.
The biggest light volume visible on the left of the Figure 5(i) has been previously optimized through an optimization that includes structural, electromagnetic and motion analysis. Such part of the design space cannot be modified during the optimization tasks and thus it has been frozen. The other non design areas are functional volumes on which the needle, the backstop and the spring act.
The load case simulates the initial condition for the motion when the armature is attracted towards the frame by the magnetic force and the spring, in the resting position. An experimental campaign has demonstrated that this is the heaviest working condition for the armature.
Moreover, since the real loads applied to such a component, are non linear and strongly dynamic and the employed optimization code [16] is not able to deal with such conditions, the authors have adopted a static optimization method. Hence, equivalent static loads have been used for the structural

optimization process. According to the above observations, the following loads and constraints have been applied:

1. a force F1 along the Y direction, with a magnitude of 2.98 N;
2. a force F2 along the Y direction with a magnitude of 0.27 N;
3. a set of constraints along the axis of the pivot around which the armature rotates, simulating the fulcrum.

It is worth to notice that in such a configuration the finite element model results partially constrained due to the allowed rotation around the pivot. In order to make the model statically determined, an advanced option of Altair HyperWorks [16] has been used. This option, named Inertia Relief, allows the simulation of unconstrained structures in a static analysis. In an inertia relief analysis, a set of translational and rotational accelerations are distributed by the code along the body of the structure. In such a way the system constituted by the applied forces and the inertia loads acting on the structure, becomes balanced.

Table 2 summarizes objectives and constraints of each topology optimization. In order to take into account the manufacturing needs, all the optimizations have been carried out by considering also a draw direction constraint for the material distribution in the Y direction, according to the reference system shown in Figure 5(i). All the optimizations have been performed by the code [16].

An interesting capability of DAeMON consists in the possibility to explore the space of hybridized solutions by removing one or more optimization constraints in the mono-optimization tasks. Such feature allows the identification of possible hybridized embodiments within a wider design space, also falling out the Pareto frontier. Looking to the mono-objective optimizations considered for the armature, the one related to the minimization of the moment of inertia presents three constraints. According to the logic of exploring the space of hybridized solutions also beyond the Pareto frontier, such optimization has been performed in the two following conditions: one considering all the constraints, i.e. an upper bound limit for mass (UB mass) of 0.332g, an upper bound limit of the armature overall displacement evaluated in the application point of the force F1 (UB Displacement) equal to 0.01 mm, the position of the center of gravity forced on the rotation axis of the armature (CoG on Rot Axis), the other considering only UB mass.

Eventually, Table 2 summarizes the performed combinations used to generate the hybridized topologies of the armature. The embodiment related to H1 has been obtained through the hybridization of the partial solutions arisen from optimization tasks 1-2-3-5, while H2 comes from the hybridization performed through the partial solutions of the optimization problems 1-2-4-5. The weights (K) assigned to each partial solutions were equal to 1.

Table 2. Performed mono objectives optimizations and their composition matrix for hybridization. MoI=Moment of Inertia with respect to the Center of Gravity; UB Mass=Upper Bound limits of Mass=0,332g; CoG on Rot axis=Center of Gravity placed on the rotation axis; UB displacement=Upper Bound of Displacement of the force F1 application point = 0.01 mm; H1, H2=hybridized topologies; grey cell means that the partial solution arisen from the mono-objective optimization has been used for hybridization.

<table>
<tr><th>ID</th><th>MONO-OBJECTIVE OPTIMIZATION TASK</th><th>CONSTRAINTS</th><th>H1</th><th>H2</th></tr>
<tr><td>1</td><td>max stiffness</td><td>UBMass</td><td bgcolor="grey"></td><td bgcolor="grey"></td></tr>
<tr><td rowspan="2">2</td><td rowspan="2">max MoI about rotation axis</td><td>UBMass</td><td rowspan="2" bgcolor="grey"></td><td rowspan="2" bgcolor="grey"></td></tr>
<tr><td>UB Displacement</td></tr>
<tr><td>3</td><td>min MoI about rotation axis</td><td>UBMass</td><td bgcolor="grey"></td><td></td></tr>
<tr><td rowspan="3">4</td><td rowspan="3">min MoI about rotation axis</td><td>UBMass</td><td rowspan="3"></td><td rowspan="3" bgcolor="grey"></td></tr>
<tr><td>UB Displacement</td></tr>
<tr><td>CoG on Rot axis</td></tr>
<tr><td>5</td><td>max difference between the work frequency and the resonant frequency</td><td>UBMass</td><td bgcolor="grey"></td><td bgcolor="grey"></td></tr>
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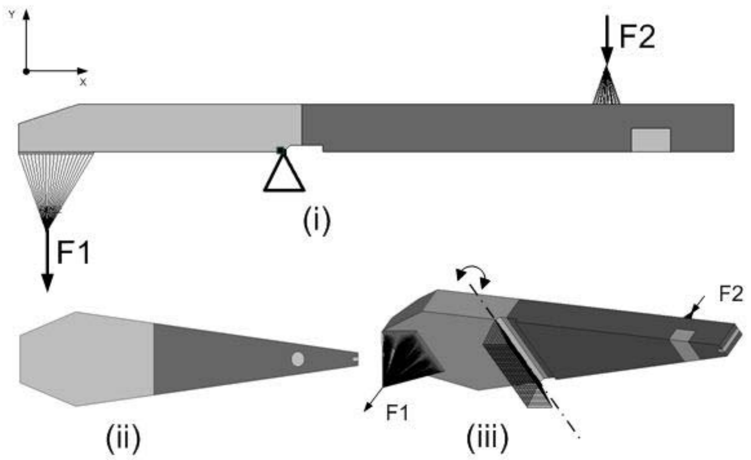

Figure 5. Domain geometry, Loading conditions and boundary conditions for the mono-objective optimizations.

3.3 RESULTS

The two hybridized solutions H1 and H2 present very similar topologies, without noticeable differences among the features. For the sake of clarity, in Figure 6 only the embodiment of the armature related to H2 is presented, together with the geometry identified by the sector experts that has been considered as benchmark. Both original and hybridized geometries have the same mass. As shown, H2 is very different from the armature designed by the experts; in fact, the latter presents a thinner central spike, while the hybridized solution has two ribs connecting the tip to the plate of the backstop.

In Figure 7 the comparison among H1, H2 and the original armature is shown, taking into account the performances related to the following properties: maximum stiffness, minimum and maximum moment of inertia and minimum first natural vibration frequency. The graph shows the performances of such properties according to a scale ranging from 0 to 1, where 1 represents the best behaviour.

Taking into account H1, it presents natural frequency and stiffness comparable with those of the original armature, while in terms of maximum moment of inertia, it has a strongly improved performance. Looking at the behaviour of H2, it presents improved performances related to the maximum moment of inertia with respect to the original armature, while the stiffness is almost comparable. Eventually the original armature has the best performance in terms of minimum moment of inertia. From these observations, it seems that the expert designers have defined an embodied solution probably giving an implicit and not expressed priority to the improvement of the performances related to the stiffness and the minimum moment of inertia.

The absence of information related to the real weights, has lead the authors to assume the performances of the original armature as implicit evaluation of the weight parameters, trying to perform a more meaningful benchmark. These values have been used in the hybridization formula, in order to obtain a weighted H2 topology. Despite, the resulting topology “weighted H2” is similar to H2, nonetheless the performance of the “weighted H2” related to the maximum stiffness appears slightly improved. Table 3 summarizes the data of benchmark among “weighted H2” and the original embodiment.

Figure 6. From left to the right: original armature and hybridized topology H2,both have a mass of 0.332 g

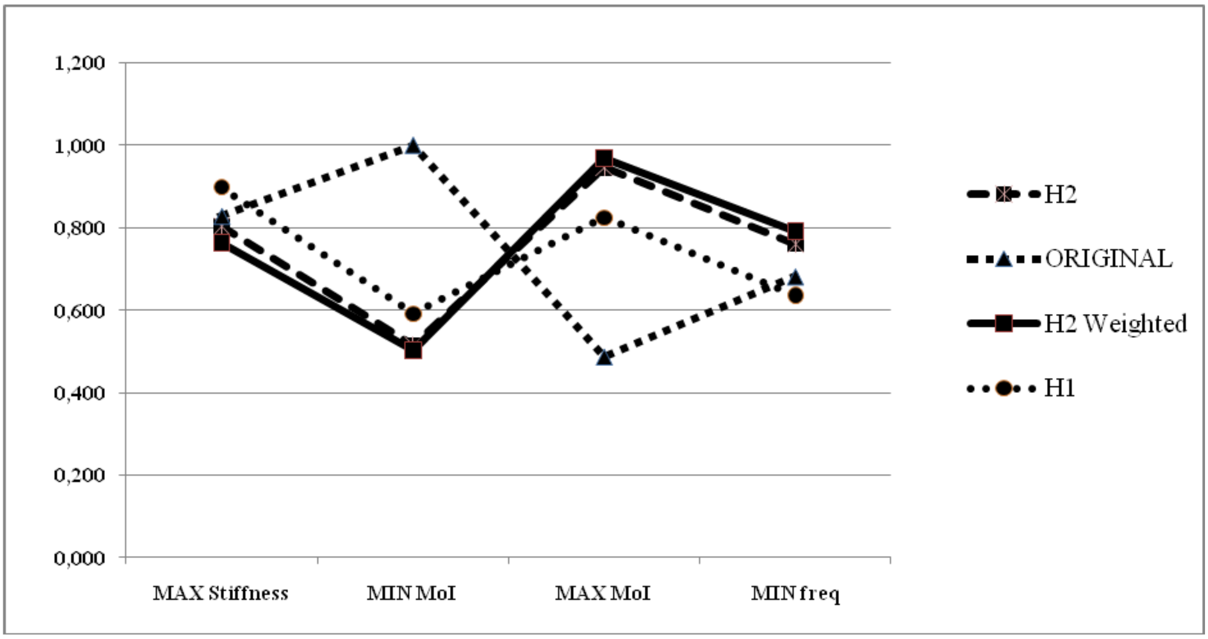

Figure 7. Benchmark among the original armature and H1, H2 and H2 weighted. Each performance has been normalized with respect the best one (1 stand for good performance, 0 stand for absent performance).

Table 3. Performance comparison among Weighted topology H2 and Original topology. S=Stiffness; MoI=Moment of Inertia; F=resonant Frequency.

Mono Objective	S	MoI (kg x mm^2)	F (Hz)	% S	% MoI	%MoI	% F
Weighted H2	4.55E+01	6.92E-03	3.65E+02	92 %	50%	100%	100%
Original armature	4.93E+01	3.49E-03	4.24E+02	100%	100%	50%	86%

4. DISCUSSION

Even if a meaningful benchmark should be performed by applying the same weights assigned by the expert designers, the hybridized embodiments arisen from the application of OTSM-TRIZ and DAeMON present improved performances for the maximum moment of inertia and minimum natural frequency, while the maximum stiffness is comparable. Thus, the proposed approach revealed to be able to guide designers having low field skills, towards embodiment solutions that comply with those obtained by the experts. Moreover, the strong difference among the shape of the original armature and those coming from hybridization, demonstrates also the capability to generate innovative solutions.
OTSM-TRIZ allows to analyze complex technical problems, highlighting the bottlenecks limiting the system performances and linking them to the system properties. Moreover, the obtained results demonstrate the great potentiality of DAeMON in performing multi-objective topology optimization tasks that the commercial software are not able to manage efficiently.
Eventually, the proposed investigation has allowed a preliminary investigation of ways for the translation of the solving directions coming from NoPa into well defined optimization tasks. It is worth to notice that the translation of the problem situation arisen from the NoPa, into an embodiment task addressed by DAeMON, is possible only when topological CPs are involved into the problem. On the basis of the above consideration, all the topological CPs identified by the NoPa can deal with DAeMON without any limit. The reproducibility of the proposed approach depends only on the goodness of the analysis made by the NoPa for the identification of the topological CPs.

5. CONCLUDING REMARKS

The paper presents the results arisen from an investigation activity aimed at implementing and verifying a possible integration among techniques for systematic problem analysis and tools for embodiment design tasks. The main objective of this investigation was to obtain some relevant feedbacks about the benefits that could arise in terms of novelty and development time of solutions. A further objective of the present research was to extrapolate preliminary rules to develop a framework merging together such paradigms.

The proposed investigation has been carried out taking into account OTSM-TRIZ as reference model to support problem analysis tasks during the conceptual design phase, while the authors' DAeMON technique has been considered as the reference embodiment procedure for the definition of the topology of the technical system. The integrated approach has been applied to the redesign of a dot printer head in order to verify its effectiveness.

The obtained methodological results have demonstrated that the NoP and NoPa models are powerful tools to identify both relevant bottlenecks limiting the technical system performances and topological properties behind such bottlenecks. The NoPa suggests the proper actions that the designer should undertake in order to improve the technical system, thus providing well defined solving directions. Eventually, a preliminary set of rules have been extrapolated to suggest how to solve the topological problems highlighted by NoPa by using DAeMON.

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