

TRIZ Future Conference 2010

Network of contradictions analysis and structured identification of critical control parameters

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Abstract

This paper aims at improving the efficiency of an inventive problem solving process for complex systems, by reducing the iterations due to the emergence of new problems caused by the implementation of the identified solution. The proposed algorithm guides the problem solver in choosing the most important contradiction to be faced with ARIZ85-C and provides further instructions about the best approach to be followed. Such purpose is achieved by organizing the characteristic parameters of a Technical System according to a specific metric, which allows both the construction of a Network of Contradictions and the definition of criteria for identifying priorities. An exemplary application of the proposed method has been carried out in the field of exhaust noise in 4-stroke engines.

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Keywords: Network of contradictions; ARIZ; Problem complexity; Computer-aided innovation;

1. Introduction

The evolution of the human society determines continuous requests of improvement of the existing technical systems (TSs), as well as the creation of new artefacts capable to satisfy new needs. These new demands frequently put the designer in front of an ill-defined situation where the goal is “almost” identified, but the way to achieve it is not clear. Then, the innovation process has to face several problems that prevent to reach the expected target. This happens mostly because of the inherent complexity which characterizes modern TSs. In fact, a great number of parameters (design variables as well as desired outcomes) with many links between them [1], doesn’t correspond to a large design space, because design constraints narrow the opportunities of obtaining the desired solution.

The Algorithm for Inventive Problem Solving (ARIZ) drives the problem solving process in any problematic situation such that two non-compatible demands must be satisfied and the space of solution seems to be empty.

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Once a Physical Contradiction (PhC) has been formulated, its overcoming often generates an invention of high level [2], but the complex nature of the problem under investigation might not allow its direct applicability.

The efficiency of ARIZ in solving inventive problems has been widely recognized; nevertheless, it allows to handle just one contradiction at a time. This may lead to a potential negative effect on the overall efficiency of the problem solving process. According to the complex nature of the problem under investigation, such process could require several iteration before the new concept of solution becomes completely applicable to the TS.

This paper investigates a new method to improve the efficiency of the problem solving process, whenever it is required to face a complex situation. More precisely, the proposed method provides directions to prioritize the contradictions emerging from the analysis of a given TS and to support the Part I of ARIZ85-C, in order to reduce the number of the above mentioned iterations and to obtain the highest benefits for the TS.

According to this aim, the second chapter briefly describes the known attempts of managing complex problems by using different problem solving methods. Chapter 3 presents the original algorithm in details, while the fourth chapter provides an exemplary application to a case study about the reduction of acoustic emissions due to exhaust noise in racing motorcycles. Chapter 5 discusses the result of the application.

2. Complex problems and solving approaches

In this chapter the authors presents a brief state of the art about inventive problem solving methods and instruments, in order to both describe models and techniques implemented in their algorithm. At the end of this chapter the specific objective of the present paper will be clarified.

2.1. Algorithm for inventive problem solving (ARIZ)

As it is well known by TRIZ practitioners, the main instrument for problem solving of classical TRIZ is ARIZ. Altshuller's last version (ARIZ85-C) is structured into different parts that guide the problem solver at:

- abstracting the problem under analysis (Part I to III);
- synthesizing potential solutions (Part IV and V);
- checking the need of problem reformulation and assessing the impact of solutions on the TS, its supersystem and other possible fields of application of the same conceptual solution (Part VI to VIII);
- reflecting on the problem solving process (Part IX).

In Part I, the Technical Contradiction (TC) behind the problem gets considered from two opposite sides in order to highlight its dichotomic nature:

1. “the improvement of requirement A causes the worsening of requirement B” (TC-1);
2. vice versa “the improvement of requirement B causes the worsening of requirement A” (TC-2).

Once that a side of the conflict has been chosen, Part II focuses the attention on the conflict itself and elicits the available Substance-Field Resources (SFR) to get rid of it. Part III completes the problem model abstraction by identifying the characteristics that the solution should have: what is the PhC to be overcome and the IFR to be satisfied.

The main limitation of this algorithm is that it deals with a single TC at a time and its efficiency may drop when it is required to solve complex problems, since the modification of some parameters of a TS often triggers the emergence of new problems.

2.2. OTSM-TRIZ instruments

OTSM is the Russian acronym for General Theory of Powerful Thinking; it provides formalized models of Classical TRIZ key concepts and introduces new instruments to organize complex problems according to a hierarchical structure, in order to identify the most critical issues. In [3] Cavallucci and Khomenko claim that one of the key issues for OTSM is to reduce the amount of problems to be solved in order to solve a complex network of problems. According to this purpose several instruments and models have been proposed to address this issue under the name of Problem Flow Network (PFN) approach.

The Network of Problems (NoP), as presented in [4], is a graph where nodes represent both Problems (Pb) and Partial Solutions (PS). Their connections provide a hierarchical structure of the problem situation together with various alternatives to solve it. The edges of the graph link the PS both to the originating problem and to the new caused problem.

The Network of Contradiction (NoC) [4] is a subsequent interpretation of the NoP and integrates information about the contradictory requirements according to the step 1.1 of ARIZ. The nodes of this network are constituted by parameters represented by Element-Name-Value (ENV) models [3], i.e. by specifying the Name of the parameter, its Value and the Element it belongs to. It is possible to distinguish parameters in the following classes:

- Control Parameters (CPs): parameters that can be leveraged by the designer in order to obtain a specific outcome;
- Evaluation Parameters (EPs): they describe the positive or negative implications of the choice of the designer.

Each elementary TC is characterized by one CP dichotomically affecting two EPs as depicted in Figure 1.

The nature of the edges of such NoC may be different. In [5] TCs are linked to each others with three different meanings:

1. Parental relationship: once the root TC has been solved the other one gets solved too;
2. Importance hierarchy: the EPs of a TC are more important than the EPs of the other TC;
3. Shared parameter: the linked contradictions share at least one parameter among EPs and CP.

On the contrary, in [4], the NoC is constituted just by links of type #3.

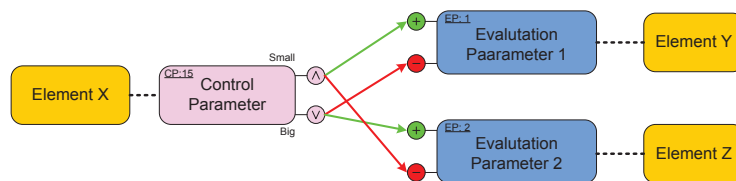


Figure 1: OTSM-TRIZ model of Contradiction, characterized by one CP (left), and two EPs (right).

The Network of Parameters (NoPa) exploits the information collected into the NoC and describes cause/effect chains in order to investigate the root causes of the emerging problems. While the OTSM-TRIZ NoC plays the role of the TC for ARIZ; the Network of Parameters plays the role of PhC, thus it can be considered as a Meta-PhC. This PFN approach is very useful to represent and model real/complex problems, but it does not provide any means in order to choose the most appropriate contradiction to work on.

2.3. Contradictions clouds

In [6], Cavallucci, Rousselot and Zanni proposed an approach that guides the problem solving process in eliciting a set of TCs. Overcoming those TCs should provide the greatest benefits according to the purpose of the problem analysis. They extract this set of TCs out of a NoC by considering three different indexes:

- Importance;
- Universality;
- Amplitude.

Importance (X_{TC})

Its definition takes into account both the impact (α_{CP}) of the CP on the couple of EPs and their importance (C_{EP}) in the scope of the analysis. The related formula follows:

$$X_{TC} = \alpha_{CP} \cdot (C_{EP_j} + C_{EP_k}) \quad (1)$$

Universality (Y_{TC})

Its definition takes into account the occurrences (QTY_{EP}) of the EPs into the body of the TCs composing the NoC. The formula to calculate Universality index is:

$$Y_{TC} = QTY_{EP_j} + QTY_{EP_k} \quad (2)$$

Amplitude (Z_{TC})

This index takes into account the quantity of EP couples that are related to the same CP in the whole body of TCs:

$$Z_{TC} = QTY_{CP} \quad (3)$$

A Cartesian coordinate systems, where each dot is related to a TC, organizes these indexes as follows:

- Importance (X_{TC}) on the x-axis;
- Universality (Y_{TC}) on the y-axis.
- Amplitude (Z_{TC}) as the radius of dots in the plane.

In [6] it is claimed that the top right corner of such diagram should collect the most promising TCs to be overcome in order to develop the system with greatest success. However, this method gives just preliminary indications about what group of contradictions should be studied and solved at first, but it leaves the final choice in charge of the person/team that has to solve the problem. The scope of the authors in [6] is to identify the most promising directions of evolution to be investigated in R&D activities; despite this is the first attempt to systematize the ranking of the contradictions met in a complex problem, this process does not take into account the implications of modifying such complex system.

2.4. Specific objective of the paper

The authors of the present paper propose a different algorithm for extracting the most important contradiction in the whole body of the NoC. The purpose is to provide a method to manage a complex problem by identifying the best opportunity for innovation of the TS. Furthermore, the method also wants to take into account the complex nature of the problem and speeding up the solving process by reducing the needs of iterations.

3. A new procedure to manage complex problems

The new algorithm to manage complex problems must help the designer from the early phases of the analysis to the overcoming of a contradiction, as depicted in Figure 2.

3.1. Information gathering phase

Starting from the emergence of a new demand, the algorithm should drive in the clarification of the initial problem situation by organizing Problems and Partial Solutions according to the NoP of OTSM-TRIZ. A preliminary version of such network highlights the lacking data and information. This lack can be compensated by retrieving information according to what is proposed in [7].

In detail it is proposed to gather such elements of knowledge by both interviewing technical experts somehow involved in the product cycle of the TS and searching in relevant sources such as patents, scientific papers, catalogues etc. The construction and the consolidation of the structure of the NoP passes through the crosscheck of the retrieved data with the directions indicated by Altshuller's Laws of Engineering System Evolution (LESE) [2]. This approach improves the capability of thoroughly investigate the problem also according to an evolutionary perspective.

Once the NoP has been validated, it is possible to elicit the characteristic parameters of the TS with the help of a technical experts or relying on the knowledge acquired during the investigation. The extraction of parameters from the NoP should be organized as follows (Figure 3):

- each sub-problem (Pb) identifies an expectation that has not been completely satisfied; at least one EP can be recognized to measure the degree of satisfaction of such expectation;
- each Partial Solution (PS) elicits at least one way to tackle a sub-problem; at least one CP can be associated to the feature exploited to address the related problem.

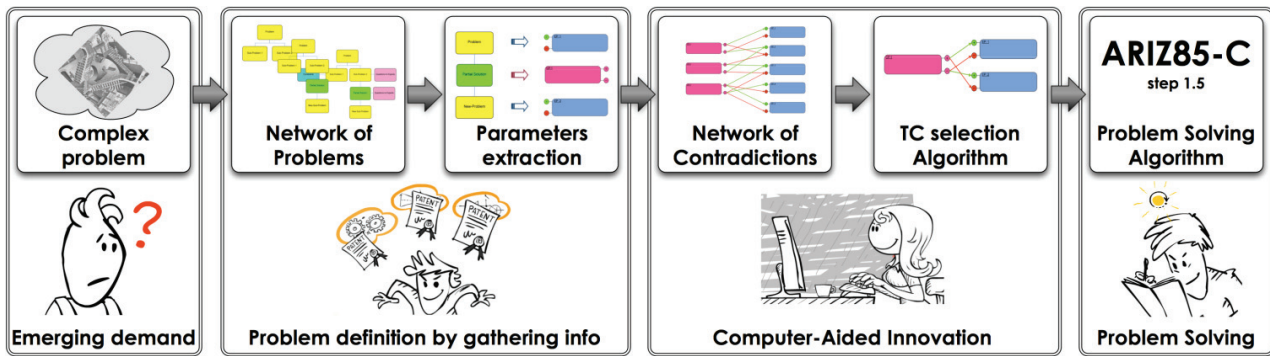


Figure 2: The main steps of the algorithm proposed to manage complex problems

3.2. Managing complex problem by NoC and NoPa

The links among Control and Evaluation parameters can be set according to their cause-and-effect relationships, consistently with the method described in [8]. These relationships constitute the basis for building a Network of Contradictions with link of type #3 (according to the classification reported in section 2.2). Furthermore, this analysis is aimed at easing the management of complex problems, which implies the identification of the most important contradiction to be faced. In order to do this, it is necessary to rank the EPs according to their relevance for the purposes of the project, then imposing links of type #2.

For this purpose, the algorithm organizes parameters according to a specific set of input variables that further details their characteristics. In detail, EPs gets clustered according to the following variables set by the user:

- *EP type*: expresses a link to the LESE #4 - Law of Ideality Increase: an EP may refer to the delivery of a Useful Function (UF), of a Harmful Functions (HF) or to Costs (C) and these macro clusters may be further sub-classified according to the criteria described in [8];
- *EP relevance (R_{EP})*: describes the importance of the parameter. The higher is the value of EP relevance (from 1 to 3), the bigger is its importance for the purposes of the project;

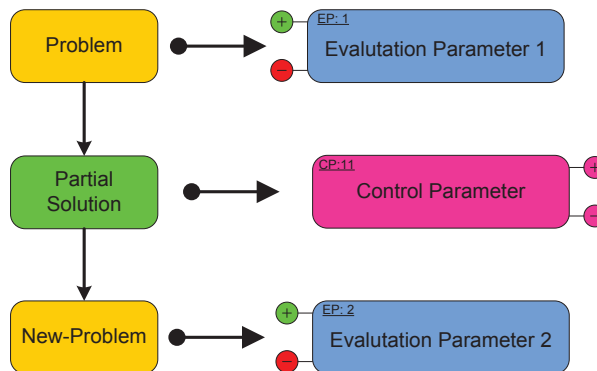


Figure 3: Parameters extraction from a Network of Problems (problems in yellow, partial solution in green).

Similarly, CPs can be organized according to the following classification:

- *CP resource*: specify what is the kind of resource (among Space, Time, Information, Material and Energy) that characterizes the parameter;
- *CP cost*: this value takes into account the economic expenses (e.g.: 3 relates to high costs, 1 to low costs) required to change current CP with a new one with better capabilities to leverage EPs.

Finally, the cause-and-effect relationship between one couple of CP and EP can be further detailed as follows:

- *Impact* (i_{CPvsEP}): describes the influence exerted on an EP by a CP. It assumes value 2 with a strong impact; 0,5 with an intermediate impact; 0 with a poor impact and 1 when the impact is unknown but present.
- *Cause/Effect relationship* (C/E_{typ}): it is a qualitative index that takes into account whether the cause and effect relationship between CP and EP is direct (+1) or inverse (-1) as depicted in Figure 4.

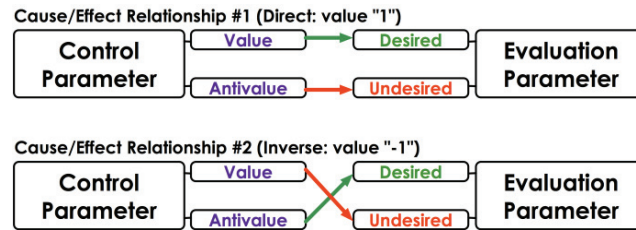


Figure 4: Example of cause effect relationships.

Starting from the parameter extraction, this algorithm has been implemented into a software application that allows the management of CPs, EPs and their mutual relationships. Then, the related NoC is automatically built according to the criteria presented in [4] and briefly summarized in Chapter 2.

Once the NoC has been generated, a new set of values has been automatically calculated and assigned to each parameter composing the TC-triads (CP, EP₁, EP₂) of the whole NoC. Table 1 summarizes with formulas and explanations the meaning of such derived values.

The algorithm for selecting the most promising TC among the whole set of the NoC is based on three hierarchical subtasks that exploit some of the abovementioned indexes. The following steps and Figure 5 summarize these subtasks:

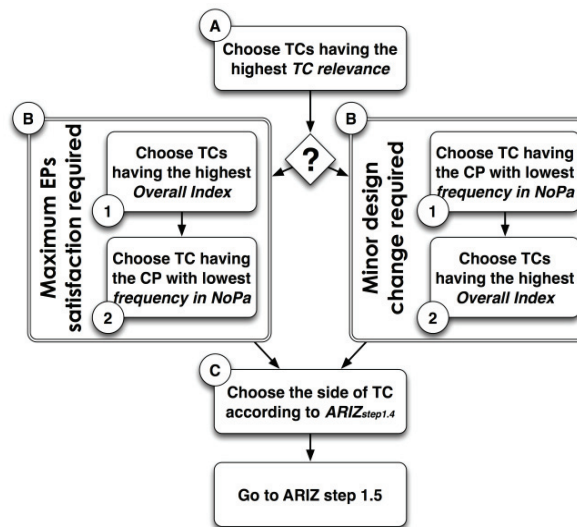


Figure 5: Flowchart of the algorithm for TC selection.

1. Extract a set of TCs having couples of EPs that provide the best results for the objectives of the problem solving process (Criterion A: Choose the TCs having the highest *TC relevance*, 6 or less).
2. Process the set of extracted TCs according to the desired level of TS modification (Meta-criterion B). When it is necessary to achieve the maximum satisfaction for both the conflicting EPs, first it is necessary to keep TCs having the highest *TC overall index* (Criterion B1) and, subsequently, choose the contradiction characterized by the CP less connected to other EPs in the NoPa (Criterion B2). Whenever

the TS requires just minor modifications, the above mentioned criteria must be taken into account in inverse order.

3. For the selected TC, define the value of the selected CP that provides the best outcomes for the whole TS and whose modification generates minimal side effects. (Criterion C: among the TCs picked out during step 2, choose the one having the highest absolute value of the – “ARIZ step 1.4 index”, thus approaching -1 or 1).

Therefore, this algorithm allows to choose just one contradiction to be faced by means of the ARIZ85-C process. The criteria are focused on achieving the best results according to the objective of the investigation (the TC must involve the most important EPs and the best leveraging CP, also taking into account the degree of connectivity of the network. Moreover, this algorithm also allows to start the ARIZ85-C process from step 1.5. In fact, the last criterion of choice (C) carries out task 1.4 of ARIZ85-C by selecting between TC-1 and TC-2 (as briefly mentioned in Section 2.1) the model of contradiction to work on during the remaining part of the problem solving process. Extreme values of “ARIZ step 1.4 index” provide the best result for the whole TS since this quantity weighs the impact of changing the value of the selected CP towards the suggested direction. According to the proposed algorithm:

- CP must take its “value” whenever ARIZ step 1.4 index approaches 1
- CP must take its “anti-value” whenever ARIZ step 1.4 index approaches -1.

Index	Meaning	#
TC Relevance	$TC_{rel} = \sum_{i=1}^2 R_{EP_i} = (R_{EP_1} + R_{EP_2})$	(4)
TC overall index	$TC_{ov.idx} = \sum_{i=1}^2 R_{EP_i} \cdot i_{CPvsEP_i} =$ $= (R_{EP_1} \cdot i_{CPvsEP_1} + R_{EP_2} \cdot i_{CPvsEP_2})$	(5)
CP (EP) freq. in the NoC	Quantity of TCs of the NoC where the CP (or the EP) is involved.	
CP (EP) freq. in the NoPa	Quantity of Cause/Effect relationships where the CP (or the EP) is involved.	
CP overall impact	$CP_{k.ov.imp} = \sum_{j=1}^{CP_{freq}(NoPa)} i_{CP_kvsEP_j}$	(6)
EP sensitivity	$EP_{j.sens} = \sum_{k=1}^{EP_{freq}(NoPa)} i_{CP_kvsEP_j}$	(7)
ARIZ step 1.4 index	$ARIZ_{step\ 1.4}(CP_k) =$ $\frac{\sum_{j=1}^{CP_{freq}(NoPa)} i_{CP_kvsEP_j} \cdot (C/E_{typ})_{kj}}{CP_{k.freq}(NoPa)}$	(8)

Table 1: Summary of the values describing characteristic indexes of TCs and the complexity of the Networks of Contradictions (NoC) and of Parameters (NoPa).

In the following chapter the proposed method for facing complex problems will be used in a real case study for reducing acoustic emissions due to exhaust noise. Comparing the consequences of choosing both the sides of the TC will clarify the logic of the proposed algorithm.

4. CASE STUDY: four-stroke internal combustion engine exhaust noise

Nowadays, the noise pollution is involving a growing number of human activities. The increase of noise level in competition vehicles has led to the closure of various circuits throughout Europe and to some problems in the motocross world championship. Historically, except for the races at the Brooklands circuit in England [9], the noise level in competitions has never been regulated. This track was made in proximity to the town and the big number of competitions produced too much noise. Just for that competition, pilots were forced to drive vehicles with a special silencer, while in the other circuits they used to adopt open exhaust systems. This system took the name: “Brooklands Silencer” (Figure 6).

Today, the problem of noisy circuits is more important because of the four-stroke oriented trend of motorcycling. Competition vehicles, especially for Motocross and Enduro, are always equipped with two-stroke (2S) engines that, at the same engine speed and displacement, are quieter than a four-stroke (4S) Internal Combustion Engine (ICE).

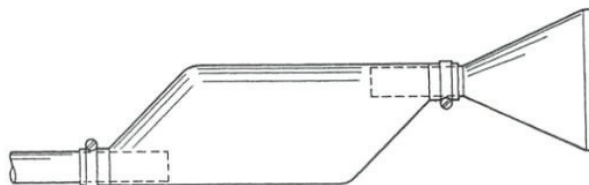


Figure 6: Brooklands silencer.

The gas-dynamic noise produced by ICE is a function of the combustion frequency and its harmonics [10]. It is worth to note that, at the same engine speed, the noise emitted by a 4S engine will have a fundamental frequency f_{ϕ} which will be halved if compared to a 2S engine. The reduction of f_{ϕ} and the increased pressure inside the cylinder has meant that 4S are noisier than 2S vehicles.

4.1. From Network of Problems (NoP) to Network of Contradictions (NoC)

The contribution to the noise of an ICE can be broadly divided into: Combustion noise; Mechanical noise; Gas-dynamic noise.

For gas-dynamics noise reduction the current technique provides a series of standard solutions for ICE [11]. The study of the standard solutions from literature and interviews with industry experts, allowed to identify Pb and PS that have been structured according to the methodology presented in [4], in order to build a NoP. The network is composed of 23 Problem nodes and 20 Partial Solution Nodes, which represent the complexity of the problematic situation. Each Pb and the corresponding PS have been analyzed in order to elicit, respectively, EPs and CPs according to what has been stated in Chapter 3.1. Furthermore, the physical phenomena that link CPs to EPs have been investigated in order to identify the related Cause-Effect Relationships. In conclusion it was possible to identify 18 EPs, 24 CPs, 53 cause-effect relationships between CPs and EPs and 29 TCs.

4.2. Application of the algorithm

It is possible to determine, according to the criteria described in 3.2, the most problematic TC.

Looking at the 29 TCs it is possible to identify those with the highest relevance, i.e. in accordance with the criterion A, characterized by the score Relevance = 6 (the highest available). The Network of Contradiction includes 9 TCs with this Relevance.

Among the latter, the selection proceeds by taking into account the Overall index and the frequency of the CPs in NoPa. In the present case study it was decided to assign priority to the maximum satisfaction of the EPs and the following results were observed:

- Overall index = 12 (the highest available);
- Freq. in NoPa = 2 (range 1 to 10).

This only TC with the above mentioned value is expressed by the following parameters:

- CP: Size of Discharge Hole;
- EP₁: Sound Vibration;
- EP₂: Flow Resistance.

Figure 8 shows weights and characteristics of the EPs and CP correlated to the TC #3, the most problematic one. The same CP impacts also another EP, the backpressure.

Figure 7 shows the three EPs related to the CP “Size of Discharge Hole”. This triad will be further used to validate the proposed algorithm.

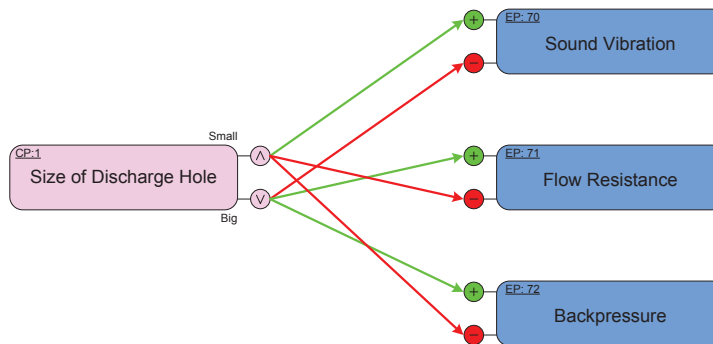


Figure 7: CP "Size of Discharge Hole" linked to EPs

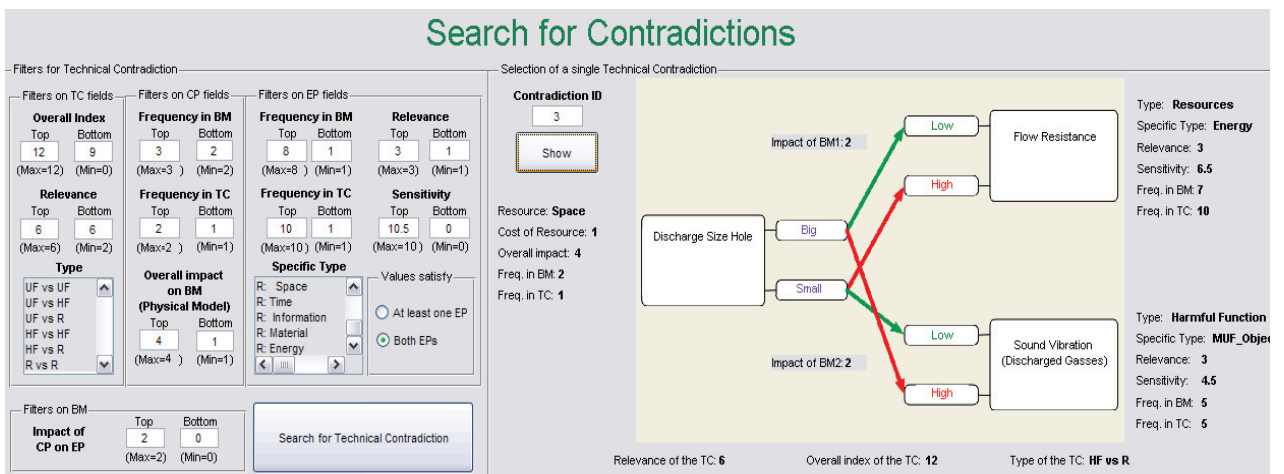


Figure 8: Search for Contradictions: parameters and weights of the most relevant TC

By means of the proposed algorithm (criterion C), the “ARIZ Step 1.4” index assumes the value -0.67 , thus suggesting to choose the anti-value for the CP, i.e. the adoption of a big hole (TC-2).

Hereafter the TC will be faced from both sides, i.e. TC-1 Small hole, thus “No gas-dynamics noise” and TC-2 and big hole, thus “No flow resistance”, in order to show the effectiveness of the algorithm. For this purpose, the generated concepts of solution will be assessed in terms of impact on the “backpressure” (EP₃).

4.3. Development of solutions and benefits

TC-2 is the first side of the contradiction to be discussed. The related ARIZ85-C process will be exposed schematically with its main steps.

Before identifying the Operational Zone (OZ) and the Operational Time (OT) of the contradiction, it is necessary to specify the Tool and the Product, respectively the Discharge Hole and the Exhaust. Referring to TC-2, the OZ is defined (Figure 9) as the area of the exhaust outlet section and its surroundings. The OZ includes the final part of the exhaust pipe, the outlet section and the initial part of the environment where the exhaust gases flow into.

The OT related to the emergence of the conflict, has been detected according to the 4S ICE working cycle, schematically shown in Figure 10 – a. The scavenging operation is only a small part of the whole working cycle, then the OT is defined as shown in Figure 10 – b. In other terms, the OT starts when the exhaust valve opens (EVO) (point 5) and ends when that valve closes (EVC) (point 6). This is repeated every 720° of crank angle and has a variable length depending on the EVO and EVC, that undergoes the influence of engine characteristics.

It is worth to mention that a 2S and 4S ICE have a different OT since the discharge cycle of the former occurs every 360° , while the latter occurs every 720° of crank angle, this implies that the OT is repeated more frequently in 2S than in 4S engines.

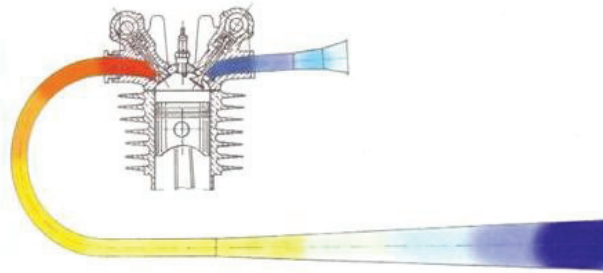


Figure 9: Schematic view of a discharge system for ICE.

The SFR have been defined according to ARIZ step 2.3:

- **Tool**
Size, Shape and Section of Discharge Hole, Gap between plates;
- **Product**
Sound Vibration, P_{amb} , P_g , T, frequency, density.

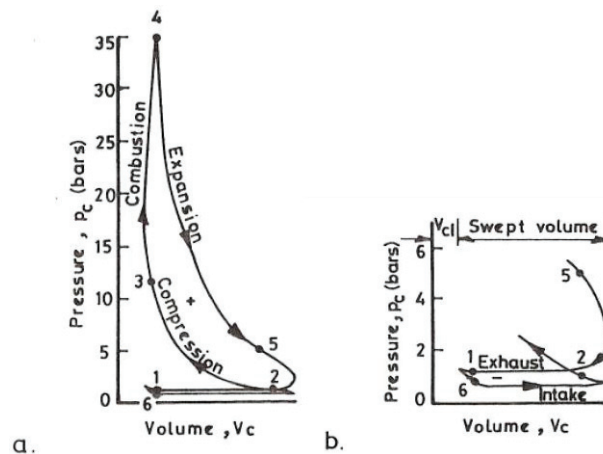


Figure 10: (a) Four stroke engine work cycle – (b) Scavenging cycle zoom [12].

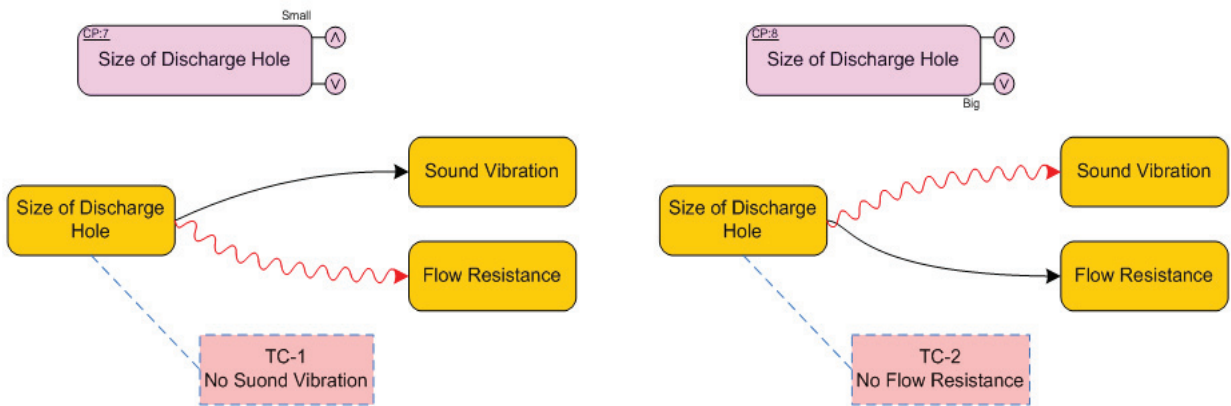


Figure 11: Two sides of contradiction – TC-1 Small Hole (left) & TC-2 Big Hole (right).

Section III allows to identify the Ideal Final Result (IFR) as follows:

<<The X-Element, without changes to the system and without any harmful effect, eliminates the gas-dynamics noise during the opening of exhaust valves in the exhaust system and keeps the capability of disposing a sufficient mass flow of exhaust gases >>

According to step 3.2, the abovementioned characteristics of the X-element should be provided by one of the SFR identified during step 2.3. The most promising choice is depicted in Figure 12.

Tool → Gap between plates

Product → Sound Vibration

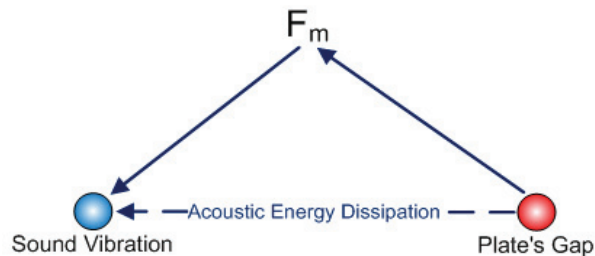


Figure 12: Su-Field model of X-element action in TC-2.

Step 3.3 allows to identify the PhC at macro level:

<<The Distance between the walls in the section between the exhaust outlet and the atmosphere must be large to ensure proper disposal of exhaust gases and must not be large to dissipate the acoustic energy>>

Note that the viscous dissipation of acoustic energy [16 pag.118] depends on the distance between the walls where the gas flow evolves:

$$h = \left[1.29 / N^{(1/2)} \right] \quad (9)$$

where h is the gap between the walls in [mm] and N is the frequency in [Hz] to be killed.

Once the Step 3.6 has been carried out, inventive standards provide directions for solution.

Standard solution 2.2.2 (Increasing the degree of fragmentation of the substance components) allowed the definition of a conceptual solution based on multiple gaps between elements, i.e. parallel plates or concentric pipes.

A potential embodiment is depicted in Figure 13.

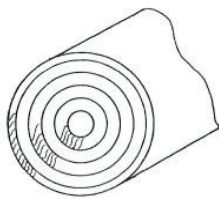


Figure 13: Concentric pipes solution.

A further analysis of the proposed solution that also takes into account the internal resources of the TS allowed to increase the degree of ideality of the TS itself. In fact, the trivalent catalyst (TWC), always present in current 4S engine exhaust systems, can be used for such purpose: the TWC could also deliver the function of reducing noise, in addition to the cleaning of exhaust gases. Currently the TWC does not reduce gas-dynamic noise since it is placed near the cylinder in order to work with gases at high temperature. Whenever the gases exit the TWC, they flow into a small section pipe where the acoustic waves compose themselves into plane waves and increase their speed, thus empowering their noisy potential. Then, the implementation of this solution requires to discharge gases into the environment directly from TWC outlet.

The concept of solution must be checked according to Part VII of ARIZ85-C by the provided control questions. In particular, the proposed solution successfully achieves the requirements of IFR-1 and, to do this, it uses the principle of viscous dissipation of acoustic energy. The proposed solution is optimized for one case, but, increasing the degree of fragmentation, its effectiveness can be easily extended. In fact, this solution is functional for a given ICE speed and, it is functional for a wider range of engine speed.

In order to clarify the benefits of the proposed algorithm, it is worth to consider the impact of the proposed solution on the other EPs affected by the CP of the contradiction, i.e., in this case, the EP₃ (backpressure).

According to the fluid-dynamic needs of the engine, it is required to have an outlet section with the same cross-sectional area of the exhaust pipe. The introduction of the TWC implies a small reduction of the outlet section, due to its nested shape, as depicted in Figure 14.

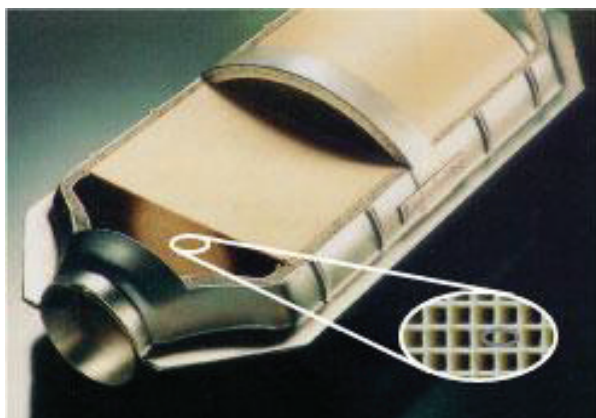


Figure 14: Three way catalyst (TWC).

The connection between the exhaust manifold and the outlet section can be embodied by adopting a diffuser that also provides some advantages for the ICE. The divergent pipe increments the amplitude of the waves of depression that are back-reflected into the exhaust pipe. The fluid dynamic effects can be exploited with success if the exhaust manifold is properly designed to obtain a better scavenging of the cylinder.

Figure 15 shows the trends of the pressure in the exhaust system [13]. This solution, besides the reduction of exhaust noise, theoretically improves the exploitation of dynamic effects in the exhaust system and reduces the level of backpressure in the exhaust manifold.

Thus, from the perspective of the generation of a viable solution, the concept generated through the proposed approach can be considered satisfactory also in terms of impact on other EPs beyond the analyzed contradiction. Nevertheless, according to the scopes of the present paper, it is interesting to check the impact on EP₃ of a solution of the same contradiction, generated by making the opposite choice at ARIZ step 1.4.

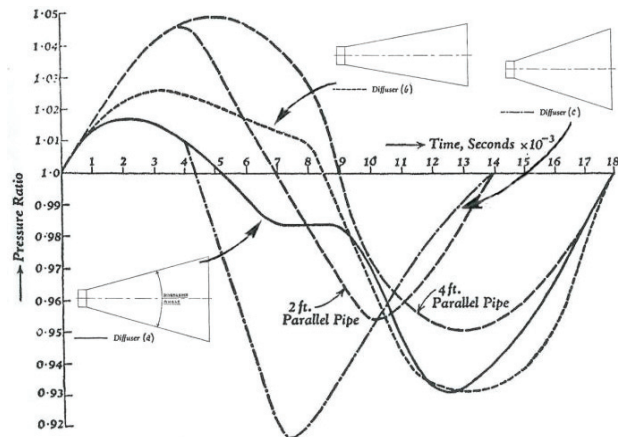


Figure 15: Backpressure in the inlet section of the diffuser - Proportions of megaphone-diffuser.

The analysis of TC-1 (Figure 11) will be briefly presented according to the solving path proposed for TC-2, specifying the Tool and the Product; respectively the exhaust pipe and the Exhaust. While the definition of the OT can rely, in this case, on the analysis of TC-2, the OZ of TC-1 has to be redefined: it is necessary to consider the whole exhaust pipe of Figure 9. It starts from the exhaust valve and ends at the outlet section, considering the whole mass of gases enclosed within the exhaust system.

In this case the IFR-1 for the TC-1 is formulated as follows:

<< The X-element, without complication of the system and without any harmful side effects, must allow the removal of the exhaust flow during the gas discharging, inside the discharge section and keeps the ability of removing sound vibration >>.

Then, according to step 3.2, the X-element has to be searched among SFR of the TS, the related Su-Field model follows:

Tool → P_{amb}
Product → Exhaust flow

The Su-Field model is shown in Figure 16.

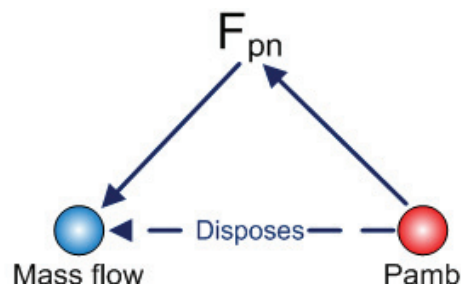


Figure 16: Su-Field model of X-element action in TC-1.

After the formulation of the PhC at macro and micro level, the inventive standards have been exploited for identifying a general solution:

- 2.2.6 – Changing structure of a substance object

In this case it is required to create a pressure reduction downstream of the exhaust pipe. The downstream “vacuum” can be achieved by various methods, such as:

- 1) Pipes carrying a pressure signal, but no mass;
- 2) Venturi’s systems;
- 3) Ejector correctly applied.

In this solution the intensification of the conflict implies the adoption of an exhaust pipe, whose outlet is “virtually closed”, and different means for exhaust removal. The estimation of the impact of this solution on the backpressure refers to the fluid-dynamic theory. It is known that the condition of having a closed outlet implies that the reflected wave pressure reaches double amplitude in that section and comes back without any reduction of backpressure. Furthermore, note that the reflected wave has the same sign of the investing wave. Theoretically, in the “outlet” section the wave reaches a peak of pressure whose amplitude gets doubled. According to Figure 17, it is possible to understand how an incident wave on a wall or on a small discharge hole tends to have a peak pressure [14]. In this case, the effect on backpressure is obviously negative, since the pressure waves store more energy at the outlet, and the level of backpressure doesn’t change at all.

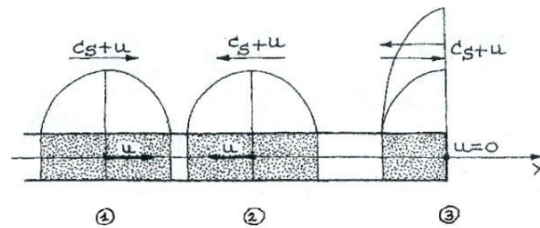


Figure 17: Positive pressure waves in a closed duct – (1) coming wave, (2) reflected wave, (3) closed section.

5. Conclusions

The present paper addresses a well known issue among TRIZ practitioners in the application of ARIZ to complex problems, i.e. problems characterized by several contradictions connected to each others. Compared to other approaches proposed in literature, a particular attention is dedicated to the reduction of negatives impacts, of the solution developed to overcome a certain contradiction, on other elements or properties of the TS.

The authors propose an algorithm to prioritize the contradiction to be analyzed first, by taking into account the relevance of the conflicting EPs, the impact on them of the CPs and their degree of connectivity to other EPs. Moreover, the algorithm suggests the side of the contradiction to be selected, with more precise directions than the step ARIZ 1.4, such that the value assigned to the CP produces the desired modification of the majority of the connected EPs. The algorithm has been illustrated by means of a practical example taken from a case study in the field of noise emission of 4-stroke ICEs. The analysis of the two sides of the chosen TC produced one concept of solution for each solving path. The assessment of their impact on the TS highlighted that the direction suggested by the proposed algorithm provides the best solution if compared to the other one.

The potential of the proposed algorithm has been shown through a relatively complex problem and with a contradiction characterized just by 3 EPs. The promising results obtained so far suggest to extend the analysis to more complex case studies, in order to continue the process of validation of the algorithm with the purpose of improving and refine its steps. Further developments are oriented towards the introduction of auxiliary criteria to take into account the resources requested by each CP, in order to weigh the selection of the contradiction to be solved considering the “cost” of the modifications. A further direction of investigation is the implementation of suggestions in critical situations such as the case in which no specific direction is provided for starting the ARIZ process, i.e. when the ARIZstep1.4 index is null.

By exploiting software capabilities, the authors are also going to integrate causal relationships among TCs in order to evaluate the related impact on the approach of complex problem solving.

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