1 TRIZ-DRIVEN ECO-DESIGN AND INNOVATION

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The paper presents a structured set of eco-guidelines based on TRIZ theory with the aim to support designer improving a product, a process or a service according with eco-parameters. Staring from a deep analysis of the original version of Laws of evolution eight operative guidelines have been deducted and integrated with other TRIZ tools related to Resource concept. Each eco-TRIZ guideline has been structured as a set of questions followed by a set of operative rules. A comparison among a selection of main conventional eco-design methods and the newly proposed TRIZ-based guidelines is described too.

Keywords: Eco-design, Green-design, TRIZ, Laws of evolution, Operative eco-guidelines.

1. INTRODUCTION

Nowadays, after centuries of inconsiderate non-sustainable exploitation of natural resources, the human interaction with environment is under the spotlight of scientists.

Forecasts about earth health are not encouraging and ecological issues are going to be one of the main concerns of our time.

From the engineering perspective, eco-design of products and production processes is the leverage to reverse the tendency and gather full eco-compatibility of industrial activity. Going deeper in detail, the challenge eco-design has to face is to perform functions to fulfill a need or to provide a benefit to the customer, while keeping into account products interactions with the environment along all the lifecycle. New eco-products, processes or services must be assessed towards their global cost that includes both economic and environment related costs.

This means that designers have to consider environmental factors in addition to the huge list of technological and market derived parameters.

Eco-design, or green-design, consists in a set of coordinated activities intended to develop more environmentally benign products and processes. Specific methods and tools are available to support eco-design and address the variety of problems.[1–9] Figure 1 portrays the most important organised by the authors according to eco assessment towards eco improvement/innovation. Methods on the left part of the graph provide practical suggestions to bring rapid changes but do not rely on a robust analysis of the system; methods positioned on the bottom are more suitable to assess as-is or to-be scenarios rather than to create new ones.

Among eco-assessment methods, Life Cycle Assessment (LCA) is the most complete and widespread one. Other tools, more or less derived from industrial experience, are more suitable for obtaining a quick advice on what to do to improve the product rather then to analyse its entire lifecycle. Some examples are Life-cycle Design Strategy (LiDS) Wheel,[5–6] MET Matrix,[6] Ten golden rules,[7] PIT method [9] and some experience-driven guidelines defined by multinational enterprises.[4,8]

The capability of performing both assessment and improving using a unique method could give advantages in terms of efficiency of work and robustness of results achieved. Relatively little research has been done on the idea generation process within Eco-innovation, and even less “Sustainable forecasting”.[10] Generally, the approach to create new product concepts or new solutions relies solely

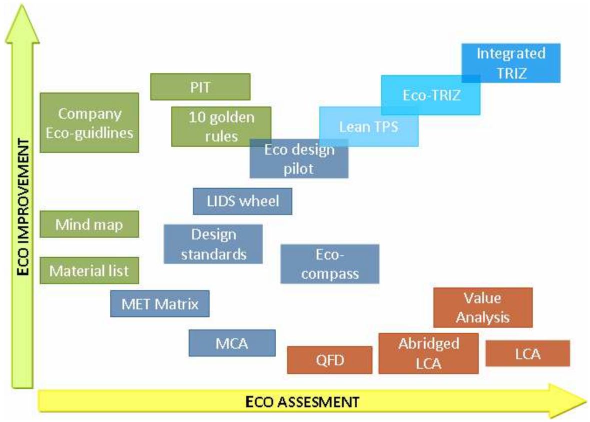

Figure 1. Eco-methods overview.

on trial and error methods. Brainstorming is often cited and it can be used with eco-design parameters bringing benefits in routine situations, but for complex or not typical problems, a structured approach to innovation should be preferred. TRIZ (theory for inventive problem solving) method can fill in the gap and boost up eco-innovation activities.

In such a context, the mail goal of this paper is to present a new set of TRIZ based operative eco-guideline to give the designers the advantage of an improved toolbox. The first part of the paper provides the description of a selection of TRIZ concepts dealing with ecology in design. The second part describes the set of eco-TRIZ guidelines elaborated by the authors. At last, a comparison among cited methods highlights common aspects as well as divergences of newly introduced guidelines towards eco-design traditional tools.

2. TRIZ TOOLS FOR ECO-DESIGN

Since TRIZ was born as a problem solving method, aiming at guiding the designer to find the right solution at the right problem according to initial constraints and criteria, every time such criteria concern eco-parameters TRIZ can be considered an eco-design method.

The attempt to integrate TRIZ tools in an eco-design framework is evident both from eco-design experts and from TRIZ community. From eco-designer perspective, a comparison among eco-guidelines and TRIZ problem solving tools (especially 40 Inventive Principles[11]) has been performed to find out similarities rather than integrations. TRIZ is perceived as a high potential method and more efficient compared to other creative methods for idea generation. Sometimes it is used in combination with other improvement eco-tools, such as Eco-Compass.[10]

Researchers from TRIZ community put particular attention to the analytical stage of assessment, not completely and effectively covered by TRIZ, at least in its classical version. This lack can be overcame by integrating TRIZ with other methods such as Lean[12–14] TPS or LCA,[15] QFD, Taguchi method, FMEA, Design for manufacture, for assembly, for disassembly, Axiomatic design,[16] etc. Moreover, laws of system evolutions are almost neglected except for the Law of Increasing the Degree of Ideality, often cited only within the TRIZ experts' community.[10]

The authors, instead, consider laws of evolution one of the milestones to face to eco-design from a TRIZ point of view. Starting from the original version of Laws by Altshuller,[17] a deep analysis focused on laws, has been conducted to answer the question: "Is TRIZ an eco-design tool?" Therefore, some TRIZ pillars have been selected and re-organised and a set of eco-TRIZ guidelines have been deducted. Laws of evolution have been chosen as a framework of this work together with Ideality and Resources due to their deep correlation. In the following, the authors briefly introduce mentioned tools.

2.1. Ideality

According to TRIZ, the *Ideal System* is a system that does not materially exists anymore, while its function is still performed. It is a theoretical concept and a powerful tool to get the necessary function without complicating the system. The ideal system is acting as pure function: it occupies no space, has no weight, does not need any energy or maintenance and it delivers benefits without harms. *Ideal Final Result (IFR)* is a description of the best possible solution for the problem situation (or contradiction), regardless of the resources or constraints of the original problem.

2.2. Resources

According to Altshuller[17] along the evolution of engineering systems, new functions were developed through the introduction of new substances and new fields of interaction. During the evolution of a system the resources for its improvement are gradually depleted, evolution slows down and inevitably the system transfers to a new level and the technical solution is replaced with a brand new one. Resources represent the key to understand how and when a system is supposed to change. In particular, TRIZ suggests to put the maximum attention to "negative" resources, those that for a traditional design approach should be removed (i.e. wastes, heat). According to TRIZ, a Resources is whatever not completely exploited available either in the technical system or in its environment.

2.3. Laws of evolution

In literature, there are heterogeneous versions of laws of evolution, varying in formulation, order and even in number.[18–21]

As said we considered the original version published in Ref. 17 by Altshuller. He subdivided the laws into three groups:

– *Static laws* describing criteria of viability of newly created technical systems:

Law 1. *Completeness of the parts of the system.* Every technical system should consist of four components: engine, transmission, control unit and working unit. If any component is missing, the technical system does not exist, if any component fails, the system does not survive.

Law 2. *Energy conductivity.* Prerequisite to viability of a system is the free flow of energy through all system parts. As every technical system transforms energy, this energy should circulate freely and efficiently through its four main parts.

Law 3. *Harmonizing the rhythms of parts of the systems.* Prerequisite to viability of a technical system is coordination (or purposeful de-coordination) of rhythms (e.g. vibration frequencies, periodicity of operation, etc.) of all parts in a technical system.

– *Kinematic laws* defining how technical systems evolve regardless of conditions (technical or physical factors):

Law 4. *Increasing the degree of Ideality of the system.* All systems evolve towards the increase of degree of Ideality.

Law 5. *Uneven development of parts of a system.* The development of parts of a system proceeds unevenly: the more complicated the system, the more uneven the developments of its parts. Uneven development of the parts is a reason for the occurrence of technical and physical contradictions and hence inventive problems.

Law 6. *Transition to a supersystem.* During evolution, technical systems merge and form bi- and poly-systems. When a system exhausts the possibilities of further significant improvement, it is included in a super-system as one of its parts and a new development of the system becomes possible.

– *Dynamic laws* defining how technical systems evolve according to technical or physical factors:

Law 7. *Transition from macro to micro level.* The development of working organs proceeds, at first, on a macro and then on a micro level.

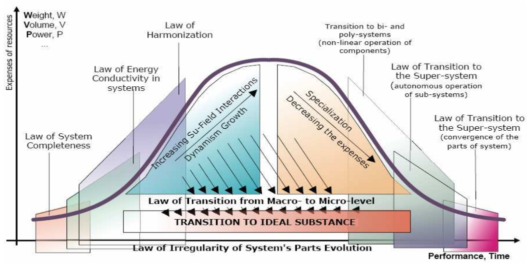

Figure 2. Generic scheme of technology evolution. (source:).[22]

Table 1. Eco-guidelines and rules.

GUIDELINES		RULES	
N.	**Name**	**N.**	**Short Description**
G1	Resources assessment	R1.1	Map resources exploitation (star daiagram)
		R1.2	Operate with minimal energy losses
		R1.3	Use only one field (kind of energy)
G2	Energy management	R2.1	Use field for which existing substances have good conductivity
		R2.2	Replace field with insufficient controllability
G3	System coordination	R3.1	Replace continuous actions with periodic or pulating ones
		R3.2	Coordinate frequiencies of fields
		R3.3	Alternate effects application/action
G4	Resource saving	R4.1	Analyse past and future system condition
		R4.2	Use ideality and IFR concepts
		R4.3	Dynamize the system
G5	System simplification	R5.1	Eliminate useless components
		R5.2	Eliminate contraddictions
G6	External resources exploitation	R6.1	Identify external resources
		R6.2	Merge technical systems
G7	Miniaturization	R7.1	Try transition from macro to micro
		R7.2	Use TRIZ physical effects
		R7.3	Apply TRIZ standard 3-2-1
G8	Fields cooperation	R8.1	Increase S-Field involvement

Law 8. *Increasing the S-field involvement.* Non S-Field systems evolve to S-Field systems. Within the class of S-Field systems, the fields evolve from mechanical fields to electro-magnetic fields. The dispersion of substances in the S-Fields increases. The number of links in the F-fields increases, and the responsiveness of the whole system tends to increase.

Figure 2 shows laws positioning according to resources consumption and maturity level of a technical system.

3. TRIZ-BASED ECO-GUIDELINES

The idea of new guidelines was born putting together the suggestion given by TRIZ laws of evolutions (such as first appearance of a technology, grow rate, etc) and by a deep analysis of resources. Re-thinking a system in terms of resources is an easily way to fix how it has been done and especially what could be any more done. Triz Laws has been considered the best tool to guide the designer choosing how to modify the system in order to tune with his evolution and exploit resources at one's best. Each eco-TRIZ guideline has been structured as a set of questions followed by a set of operative rules. Table 1 summarizes the suggested guidelines and associated rules.

G1. Resource assessment

How much energy has been employed in order to provide the main useful function of the system compared to the other auxiliary functions, wastes compensation, control parameters? Does the technical system allow through passage of energy? Is there good conductivity between the parts and the control units?

R1.1. Map the resources exploitation of your system. Resources are analyzed one by one separately. For example: taking into account a building, energy (E) can indicate the yearly energy requirement (class A+ = 40 KWh/m^{2}y) whereas for a household appliance can be the power absorption (in W);

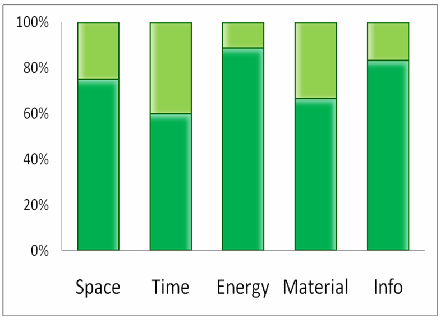

Figure 3. Resource assessment.

Space (S) can be the overall occupied volume (in m^3) or simply the surface dimensions (in m^2), Time (T) is the utilization period (in seconds) or the entire life (in years).

R1.2. Technical system should not only be a suitable power conductor but should also operate with minimal energy losses (such as losses incurred by transformation, production of useless wastes, and withdrawal of energy with ready-made artifact). System should use energy only to provide the main useful function in according to IFR concept (for instance during a sterilization activity using an hot peracetic acid distinguish and compare the minimal energy useful to kill a bacterium with energy used to create, to move, to heat and finally to atomize the acid onto the bacterium).

R1.3. It is desirable to use one field (one kind of energy) for all process of system operation and control. As the technical system evolves, every new subsystem should use energy that circulates in the system, or energy that is available free of charge (energy of the environment, wastes of another system). You should act according to the "Reduce Energy conversion to zero" Trend of evolution (e.g. steam train used chemical energy to heat, to pressure, to mechanical; diesel train chemical energy to pressure to mechanic, electric train electrical to mechanical, Magnetic train use only magnetic effect of electric energy to move).

G2. Energy management

For which field do substances of the technical system have the best conductivity? Is it possible to use a more controllable field? What field (already present in the technical system or freely available) can be best used for the new subsystem?

R2.1. If the technical system consists of irreplaceable substances, it is necessary to use field for which the existing substances have good conductivity (to operate at cellular level use biological field or chemical instead of mechanical, to seal high pressure vessel choose mechanical field instead of electric or magnetic etc.)

R2.2. If the substances of the parts can be replaced, then the field with sufficient controllability should gradually replace the field with insufficient controllability in the following order: gravitational, mechanical, thermal, magnetic, electric, and electromagnetic. Replacement of fields is carried out together with replacement of substances or introduction of the admixture that secure good power conductivity (the substance should be transparent for the chosen field).

G3. System coordination

Are the parts of the system opportunely coordinated?

R3.1. Replace continuous actions with periodic or pulsating actions, and then to resonant so that the technical system operation is optimized through mere modification of its component (dimension, mass, and frequency). Nothing is introduced into the system in order to improve the main useful function and efficiency according to the energy conservation. The frequencies of vibration, or the periodicity of parts and movements of the system should be in synchronization with each other (e.g., traffic light coordinated with the exact amount of cars moving on the streets, lamps turns on only when someone enters a corridor or an elevator or opens the door of a fridge), or coordinated (or de-coordinated) with natural frequency of the product. For example, microwave use the water dipole vibration to heat their molecule instead of heat by thermal source, pulsating water jet at the resonance frequency of the bottle is possible to clean it reducing jet pressure and water temperature, high frequency pneumatic rock drill increase the useful effect reducing the blow.

R3.2. Frequencies of fields used in technical systems should be coordinated or de-coordinated (e.g. use a noise active barrier producing a coordinated anti-wave to neutralize noise).

R3.3. If two effects are incompatibles (e.g. transformation and measurement), one effect should be exerted when the other effect pauses. More generally, a pause in one effect should be filled by another effect (e.g., teletext systems hide data between the frames of TV programs).

G4. Resource saving

Are there inside the system new or not fully exploited resources?

R4.1. Analyze past and future condition of the system, its components and environment to identify all kind of potential resources hidden in the system (instead of waste exhaust gas from an engine put in again into the engine to create a turbo effect, use body energy due to vibration during a march to recharge equipment's batteries etc.).

R4.2. Use IFR method and Ideal System concept to radically modify your system. Using free or available resources, eliminating the deficiencies of the original system, no elements are introduced into the system, and the system does not get more complicated. One of the elements of the system or environment eliminates a harmful effect, preserving the capacity to produce a useful effect all by itself. For instance, in order to dematerialize the product some traditional mechanical lawnmowers are experimenting with "smart grass seed", grass that is genetically engineered to grow to an attractive length, then stop growing.

R4.3. Dynamize the system: to improve their performance rigid systems should become dynamic i.e., pass to a more flexible, rapidly changing, and adaptable structure.(e.g. blade cut, flexible cut, water cut, laser cut)

G5. System Simplification

Is your system in evolution or in convolution trend?

When a new system appears, at first complexity raises up and resources exploitation is inefficient, uncontrolled, and not harmonized (expansion phase). Afterward, energy consumption tends to be optimized; global efficiency grows while system is simplified by trimming components and transferring functions to the supersystem.

R5.1. If they exist, eliminate useless components.

R5.2. Eliminate contradictions due to the uneven development of parts of a system using traditional TRIZ Separation Principles.

G6. External resources exploitation

If the system already reached its maximum development, it will aim to delegate functions from inside the system to outside to the super system; next step of development continues at super system level, i.e., the environment around the system.

R6.1. Individuate external resources by analyzing system environment in past, present and future times (e.g. use underground thermal capacity to create natural ventilation in the house, sprinkling a shrub by colored water avoids the use of paint to color wood panel after, etc.).

R6.2. Merge technical systems and anticipate bi- and poly-systems forecasting schema (e.g. in terms of efficiency, two (or more) blade razors cut better than passing twice (or more) a single blade razor).

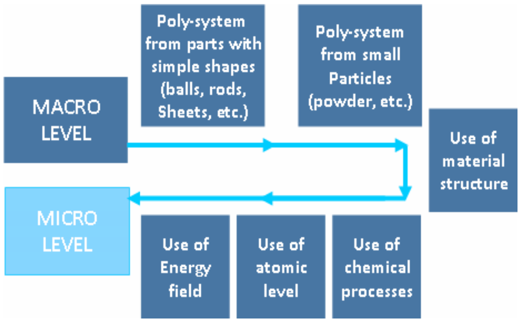

Figure 4. TRIZ classical macro to micro evolution steps.

Table 2. Eco-design methods comparison.

Areas / Methods	Material selection	Resource consumption	System efficiency	Longlife, recycling, upgrading
Ten Golden Rules	1. No toxic substances or close loops 7. Invest in better material	Minimize energy and resource consumption in: 2. production and transport; 4. usage phase 3. Invest in better material	4. Minimize energy and resource consumption *in the usage phases*	5. Promote repair and upgrading; 6. Promote long life; Prearrange (8.) and promote (9.) upgading, repair and recycling
Brezet's check list	Question of the "Production and Supply of Materials and Components" sections, e.g. how much, and what types of X-materials are used?	Questions of the "Utilization" section, i.e. how much, and what type of consumables are needed?	Need Analysis: does the product fulfil functions effectively and efficiently? Utilization: what problem arises when using, operating, servicing and repairing the product?	Questions of the "Recovery and Disposal" section, i.e. can the components be disassembled without damage?
LiDS	Environmental oriented selection of materials	Reduction of material consumption	Reduction of the environmental impact of production and during use, distribution optimization	Increase of the useful lifetime, optimization of end-of-lifesystem
Eco Compass		Resource conservation, renewability of materials, energy consumed	Optimization of production techniques and distribution systems, reduction of impacts during usage	Revalorization, remanifacturing, reuse and recycling possibilities
PIT		Reduce amount of material, reduce water and energy usage	Function Re-design	Extend product lifecycle, design for longer life, reuse components
Companies guidelines	Lists of materials (White, grey, black)	Materials Declaration Questionnaires		
Eco TRIZ Operative Guidelines	Function-based materials, no prior limitations	1. Resource Assessment 4. Resource Savings 6. External Resources 7. Miniaturization	2. Energy mgmt 3. System coordination 4. Resource Savings	self service principle (self- repair,self maintain,self-x)

G7. Miniaturization

Is the tool completely under control? At what physical scale does the tool interact with the product of the system?

R7.1. To implement system development try a transition from macro to micro level, maintaining the same function.

R7.2. Use TRIZ Physical effect and Phenomena database.

R7.3. Apply TRIZ Standard 3_2_1:

Efficiency of a system at any stage of its evolution can be improved by transition from a macro level to a micro level: the system or its part is replaced by a substance capable of delivering the required function when interacting with a field".

Figure 4 portrays the most recurrent steps in the direction of miniaturizing parts interaction. For example to lower the level joining two elements means starting from nails and screws to connections by surface tension, welding, soldering, glues, thermonuclear synthesis, isotope synthesis, till to electrostatic field connection.

G8. Fields cooperation

R8.1. Develop the system increasing the S-Field Involvement

Eco-TRIZ guidelines have been compared with state of the art tools for eco-design.

To evaluate different tools on a common base, topics regarding sustainable design have been defined and for each of them, suggestions of TRIZ and Eco tools have been reported. Main topics are: (i) Material selection; (ii) Resource consumption; (iii) System efficiency; (iv) Long life, recycling, upgrading. Table 2 summarises the evaluation.

4. CONCLUSIONS

TRIZ methodology has been evaluated as a potential allied for exiting eco-design methods. Some TRIZ tools, such as Ideality, Resources and Laws of technical evolutions, have been re-organized in the form of practical eco-guidelines for product innovation and compared with the state of the art tools for eco-design. Traditional tools for eco-innovation consist in a more or less structured set of prescriptions to be taken into consideration to decrease product impact on environment. They are generic advices or strictly related to a specific industrial field. The main benefit of TRIZ in eco-design consists in providing guidelines that have either a general value and provide detailed prescription to increase product sustainability. The fundamentals concepts of Ideal Final Result and Resources are applicable to any system at any level of detail, while laws and rules derived from the original formulation have been translated into practical guidelines to systematically eco-innovate. On the other hand, TRIZ approach can benefit of the assessment phase, mainly performed with LCA, in order to frame the problematic situation to be addressed.

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