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A pioneering project on laser pyrolysis based entirely on TRIZ

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Abstract. This work presents an application of the TRIZ methodology to an industrial project dealing with laser pyrolysis of tires, bitumen, and other wasting materials. Usually in the literature you can find works that describe how to apply TRIZ to single cases of problem solving, to conceive new products or to strategic planning activities. In this paper instead we present a methodological approach that combines the use of different TRIZ tools to support an entire industrial project. Triz tools will be briefly introduced to show how they can be used to decide between different industrial pyrolysis technologies, identifying strengths and weaknesses of existing laser applications, suggesting patents around the existing idea, designing the innovative idea of a laser chamber to test the effectiveness of the process.

More in details, the evolution trees and the macro-micro law of technical evolution were revisited and suggested for analyzing and organizing results of a big search about the state of art. Contradictions and Ideal Final Result were used to analyze existent products and design the new ones. TRIZ methodology is also useful for building a storyboard able to convince other stakeholders of the credibility of the results and to create a team of companies and academics willing to invest in such a pioneering idea.

Keywords: TRIZ, Evolutive trees, Laser pyrolysis

1 Introduction to the pyrolysis process

Waste disposal has been considered a major problem worldwide for several years and, without urgent action, is expected to worsen in the future, with an estimated seventy percent increase in global waste by 2050 [1]. The organic fraction alone constitutes almost half of the total waste. A quarter of the organic fraction is incinerated, by exploiting in most cases the traditional plants. However, pyrolysis is becoming increasingly popular as a valid alternative because of the economic convenience of installation and management. The scalability and portability ensure this process to be exploited in

contexts where traditional incinerators cannot be applied. The environmental sustainability is improved due to the lower generated pollutants and the recyclability of its products for other uses or for energy generation [2].

Pyrolysis consists of heating different types of organic wastes (e.g. biomass, paper, tires) in the absence of oxygen or other oxidizing agents to obtain their thermochemical decomposition, obtain three types of products, i.e. a solid fraction (char), a liquid fraction (bio-oil, tar) and a gaseous one, characterized by the discreet presence of carbon and hydrogen which give it a valuable calorific value. In addition to the treated waste, the proportion between the three products of the reaction depends by the combination of the following parameters: reaction time, reaction temperature and heating rate [3].

Since the 1970s, a wide range of pyrolysis technologies has been introduced both experimentally and commercially, which explored many combinations of treated waste, reaction parameters and structural solutions. This activity has also been documented with tens of thousands of scientific publications and patents, with a clearly growing trend in recent years. However, for those who want to adopt pyrolysis as an alternative means of treating waste, finding their way through the different technological options is a very difficult task. In fact, even just from a preliminary reading of the sources, all the complexity of the problem emerges, which is characterized by a great variety of factors to consider, which are mutually dependent. Among them, there are: the type of waste in terms of chemical composition, the degree of conservation e.g. percentage of humidity, and state of aggregation, e.g. granulate, pellets, waste; the already mentioned parameters of the reaction; the characteristics of the reactor in terms of exploited physical principle, layout, materials, dimensions, costs, performance, reliability and portability; knowledge and availability of information about the process and the plant, with plenty of combinations still unexplored.

There are many technologies at industrial level for pyrolysis process; the first step of this work was to analyse all of them to understand which was the most promising, then it was defined a criterion of choice based on the scientific literature available. The result of this investigation highlighted the advantages of laser technology. Hence a second in-depth study was used to understand the pros and cons of this technology and then propose an innovative solution and a series of tests.

The intent of this article is to demonstrate how TRIZ can be used across the board at every stage of the process.

2 TRIZ PROJECT

This paper discusses an industrial project on laser pyrolysis conducted by a team of individuals from academia, consulting, and industry all sharing experience on TRIZ methodology.

The group with the greatest experience in TRIZ is headed by the group of researchers from the University of Bergamo, where the scientific head has over 15 years of experience in TRIZ consulting and training, 20 international patents and over 100 product innovation products for companies of different industrial fields and can rely on an experienced team including a post doc with 8 years of experience and numerous patents.

The most specific knowledge in the field of pyrolysis is held by Paolo Peri who also participated in the creation of hot spheres pyrolysis reactors that in the past had collaborated with external TRIZ experts in many consulting projects, also finalizing 3 patents.

The specific expertise on laser and chemical-physical experimentation has been entrusted to the research group of the University of Lancaster; the academic who now follows the project had collaborated several times in the past in TRIZ projects together with the University of Bergamo and with companies in the area. Finally, the technical expertise on design and prototyping is in the hands of the engineering consulting company YTD, where the owner has recently become a TRIZ practitioner. following over 40 hours course and several TRIZ based case studies on the last 2 years.

The main objective of this project is the development of a new innovative technology for the transformation of industrial production waste into valuable gases such as methane and hydrogen, with a very low production of waste ash.

The main idea around which the Project revolves around is a laser treatment conducted in a special chamber that allows to obtain re-heating speeds higher than any other technology ever produced but with a gasification process at room temperature to preserve the cleanliness of the process area. The way to overcome this contradiction, a hot and cold laser chamber was patented, first filing a European patent application recently extended to an international PCT application WO2019159088 [4].

The methodology used for the development of this project is entirely based on TRIZ. In fact, the methodology was used to:

- identify the best pyrolysis technology, and most strategic parameters to obtain hydrogen and methane gases.
- identify open problem in laser pyrolysis, assessing the maturity level of existing solutions and main contradictions to be overcome.
- design a new laser chamber for testing its efficacy.

In the following article, each step of the methodology is explained in detail with reference to the use of TRIZ tools and the results obtained.

3 Methodology

This paper proposes a use of TRIZ, to (1) select a technological option, (2) identify its open problems, and (3) design a concept to implement it. However, this use is not a pure application, since it involves a rethinking of a TRIZ tool at a methodological level in the first phase.

In fact, the proposed evolutionary framework of the technologies differs in fact from the evolutionary tree of Shpakovsky [5] since in it there is a miniaturization of a structure and not of the operational area of realization of the function, as in our case. The main advantage is that this modification allows to compare concepts on the basis of their behavior rather than their structure and therefore to be carried out in the early stages of the design, i.e. when the structure has not yet been associated with the behaviour to realize, following the order established by the FBS design framework [6].

4 Results

4.1 Using TRIZ to identify the best pyrolysis technology

The starting point of this activity was the recovery of knowledge relating to the ways of performing pyrolysis from the main reference reviews on the subject (i.e. [7], [8], [9]). In this way it was possible to identify the main technologies of pyrolysis plants, understand their basic operation, the main advantages and disadvantages and provide a first classification at a structural level.

The most common classification of these macro-level technologies is that relating to the type of heat carrier used to pyrolyze the raw material. In the fixed bed reactors, the vector is constituted by hot particles of small dimensions, such as sand, which remain lying on the bottom of the reactor and are invested by the raw material which falls on it by gravity. In a less common variant, hot plates are used directly as a heat carrier. In fluidized bed reactors, the same particle heat vector is set in motion inside the reactor by a pneumatic flow to facilitate mixing and heat exchange with the raw material. There are also reactors in which hot spheres which act as heat carriers are mechanically moved by means of an auger or rotating cone. Finally, there are reactors that use radiation as a thermal vector, including plasma and lasers.

Fig. 1 provides an overview of the main pyrolysis technologies.

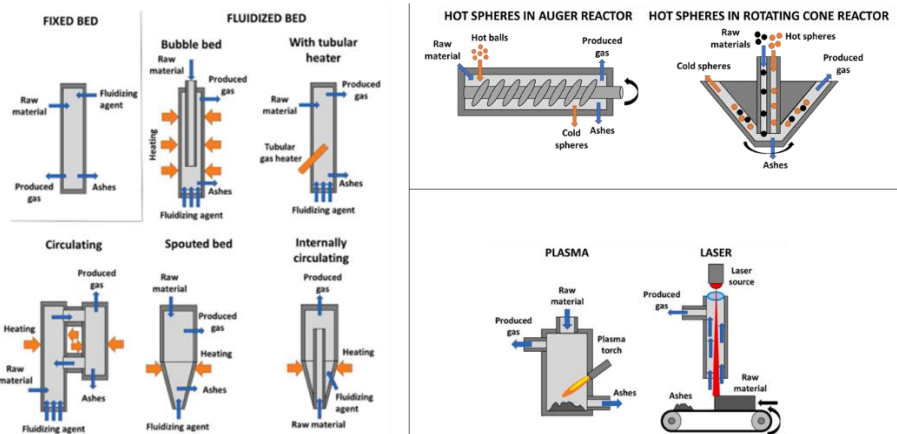


Fig. 1. Main pyrolysis technologies.

TRIZ was then used to order the different pyrolysis technologies according to an evolutionary criterion and to understand, in this perspective, which was the best technology. The approach used consists in using principles of the evolutive tree theory of [5].

The evolutionary tree offers the organizational structure suitable for creating the hierarchy of content, allowing a high-level strategic vision within which to organize any other classification. The mechanisms on the main branch are ordered based on the TRIZ pattern "Evolution toward the Micro-level and Increased Use of Fields" explaining that

technological system tends to perform its main function by going from a macroscopic to a microscopic level, increasing the use of energy fields, to improve performance and increase control of its operating mode.

The starting point is the Minimal Technical System model [10], which requires establishing the main function, who receives the action and the tool entering into contact with the Object to perform the Function. The interface between Tool and Object is therefore considered, analysing the way in which the main function is exchanged. In this case, the Object or entity that is pyrolyzed, whose description can be limited to the generic term "waste" or to a specific material or product, e.g. cellulose, waste tires, cherry pellets; the Product, or the transformed object, i.e. the pyrolysis product, e.g. char, tar, gas, electric energy; the Tool or the material/intangible entity, e.g. hot auger, microwave, of the Technical system (i.e. the reactor) entering into direct contact with the Object to perform the Function, i.e. heat transmission.

The basic classification scheme proposed to classify results has a tree structure with a trunk and several branches. The trunk collects the main heat transmission mechanisms of heat transmission of pyrolysis which are described by the pair of the Tool transmitting the heat, e.g. hot plate, hot balls, microwave, and the Object receiving it, i.e. waste. While the branches branch off from each mechanism of the trunk and group its main technological development trends, each of which aim to solve a distinct function, e.g. improving the Tool heating, moving the raw material. The heat transfer mechanisms on the trunk are ordered on the basis of the TRIZ Law No. 7 "Evolution from macro to micro-level and greater use of fields" explaining that technological systems, when they evolve, tend to perform its main function by moving from the macroscopic to the microscopic operating level by increasing use of energy fields, performance and control. In relation to this trend, the heat transmission mechanisms have been ordered based on their ability to involve a growing portion of raw material, i.e. waste, in the exchange of heat, perfecting the degree of interaction. In this way, by refining the control more widely, the interaction can become more complete overall: it is one thing to heat a surface by contact, another to interact directly with a molecule. Consequently, this line of evolution leads to a progressive segmentation of the Tool transmitting the heat through a reduction in mass, e.g. moving from the hot spheres to the hot particles and its dematerialization, e.g. passing from the hot particles to the electromagnetic waves.

The result of this classification, reworked from an initial attempt that had been outlined in [11], is represented in Fig. 2, showing the classification of the pyrolysis heat transmission mechanisms on the trunk of the evolution tree.

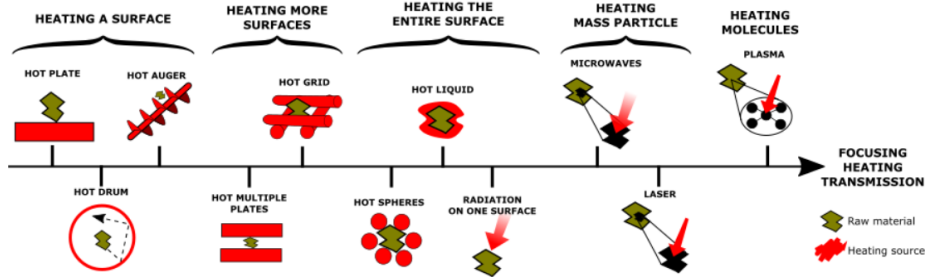


Fig. 2. Classification of the heat transmission mechanisms of pyrolysis on the evolution tree trunk, ordered according to the increase in the focus of the interaction with the raw material (waste).

The verification of this hypothesis was carried out with a purely bibliographic study [12], where over 89,000 documents between scientific journals and international patents were analysed to identify main technologies for material pyrolysis (i.e. fluidized bed, hot balls, microwave, plasma, and laser), compare them in terms of technical performances and discover future trends.

The time distributions of the annual publications related to the different technologies for pyrolysis, both in relation to the various processed materials and at an overall level, highlighted the consolidated interest in fluidized bed and hot spheres, with a net growth that began about twenty years ago and is settling at constant values in the last decade, while plasma and laser are still in an embryonic phase, with a growth that has not yet begun.

The average innovation index of technologies is growing from fluidized bed reactors to lasers, with a clear gap between radiation-based and other technologies.

The average heating rate and the average reaction temperature of the technologies increase passing from the fluidized bed to the laser, both in patents and papers and this trend manifested itself mainly thanks to the contributions of the last decade (see Fig. 3).

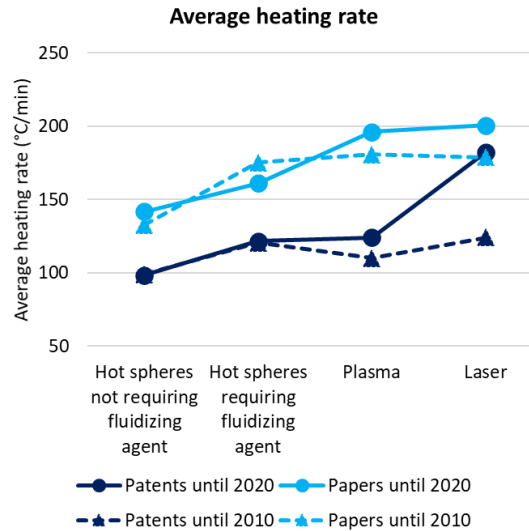


Fig. 3. Classification of the heat transmission mechanisms of pyrolysis on the evolution tree trunk, ordered according to the increase in the focus of the interaction with the raw material (waste).

The use of TRIZ in the early stages of design is possible and has only recently been formalized (e.g. [13]). What is proposed is conceptually placed downstream of the approaches in the literature since, unlike them, its objective is not the collection and organization of design requirements. A first hierarchy of ideas on an evolutionary basis (step 1), based only on the miniaturization of the operational area where the function is performed, is instead proposed. In our opinion, in order to structure a guideline for the concept selection, the functional concept hierarchy must also be confirmed by the comparison with the structural parameters and with the performances of the different concepts, as shown in Figure 3 (step 2). Therefore, a further confirmation should be sought in the comparison of the evolutionary trend with the design requirements (step 3), appropriately organized, e.g. as was done in [13].

4.2 Using TRIZ to identify open problem in laser pyrolysis

Having noted the advantages of lasers over other pyrolysis technologies, our study turned to identifying the problems of this technology that must be overcome to ensure its application in waste disposal.

Following the TRIZ-based approach outlined in [14], it was possible to automatically extract typical laser pyrolysis functions and application fields from the pool of its articles and patents, extracted from the overall pool described in Section 3.1.

According to this approach, we look at who has already solved the problem in their industry to start from the most advanced solution and then identify the contradictions and resolving it to evolve towards Ideal Final Result. The analysis of the sector has

helped to find the main requirements and problems and to know the technological prior art needed for bypassing existent patents.

The result of this analysis, i.e. the comparison of functions, fields of application and types of lasers used for pyrolysis, are shown below in Table 1.

Table 1. Comparison between application fields, laser pyrolysis advantages and preferred types of laser for pyrolysis.

Application fields	Laser pyrolysis advantages	Preferred types of laser
Chemistry	Producing catalytic particles and coatings with microstructural and chemical properties optimization	Pulsed CO ₂
	Maximize the production of nanostructures	Continuous CO ₂
	Realizing bimetallic coatings to increase the catalytic properties	CO ₂
	Increasing the mass production of ethylene	IR
	Reducing the energy consumption during the production of light olefins	CO ₂
Electronics	Increasing the electrical and magnetic properties of silicon oxides nanopowders used for semiconductors	Nd: YAG
	Increasing the control over the thickness of coatings/deposition layers in integrated circuits	Nd: YAG
	Improving the insulating properties of ceramic coatings	Nd: YAG
	Improving the photoelectric properties of particles and coatings used for solar cells	CO ₂
Electrochemistry	Increasing the life of the carbon nanoparticles that make up the membranes of fuel cells, and consequently their durations	CO ₂
Biomedical	Producing drug coatings with greater and more controlled biodegradability	CO ₂
	Making nanopowders to treat cancer in a more localized way	Pulsed CO ₂
	Optimizing the surface finish of prostheses so that they can weld with bone in a shorter time	Pulsed CO ₂
Waste treatment	Improving the properties of the syngas produced by the waste pyrolysis	Pulsed diode
	Improving the efficiency and reducing the process times	Pulsed diode

Finally, with this work it was also possible to identify already existent laser pyrolysis technologies that have already been proposed to process waste within the literature:

- RU2403499 (2009) Installation for recycling organic wastes and oil sludge. The laser is applied only for pre-heating of waste, while the core process inside the reactor pyrolyzed waste by molten salt heating and not by laser.
- US3652447 A (1969) Process for extracting oil from oil shale. The manure passes on a conveyor belt inside a chamber without oxygen and is invested by the laser and by pyrolysis produces bio-oil.
- WO2018/186958 (2018) Methods and systems to produce crystalline flake graphite from biomass or other carbonaceous materials It deals with the pyrolysis of manure and another biomass by laser. The goal is to obtain certain compounds (crystalline flake). However, the scale is laboratory, and the objective is not to dispose of the waste but to create compounds.

4.3 Using TRIZ to design a new laser chamber

3.3.1. Overall scheme

The use of TRIZ in the design of the new laser chamber has been subordinate mainly to the improvement of its design through the resolution of the various contradictions that have emerged gradually.

In particular, the most significant problem that has been solved concerns the protection of the laser source optics. This element is the most critical element of the system since when it gets dirty the operation is compromised and this happens when the splashes of molten material that is being pyrolyzed soil the optical components, thus acting as seeds for extra undesired heating that would affect the optics themselves. The contradiction in this case is given by the necessity to guarantee at the same time the two following evaluation parameters:

- EP. 1: shield the optics from molten splash.
- EP. 2: leave the flow of the laser free to pass through the lens.

Rapid heating of the material during pyrolysis leads to a real explosion, which dirties the chamber and especially the laser optics. If the reaction temperature is not hot enough, the desired pyrolysis reaction will not occur, and the desired gases will not be produced. We therefore want a cold and hot chamber, a vigorous but clean process, shielding media vs. no walls in the chamber.

The solution is given by a combination of many ideas where the necessary resources to ensure pyrolysis such as nitrogen flushing and vacuum act synergistically respectively as a barrier for splashing and to remove gaseous particles before their recombination respectively. In addition, this is used to remove the oxygen from the zone of interaction. All of this takes place in a very confined operating zone consisting of a channel coaxial to the laser flow.

Since the syngas produced in this condition is not transparent to the laser, it must be removed immediately. For this reason, when the syngas transits in this zone, it creates a high efficiency gaseous barrier, in a cold chamber where a localized reaction takes place at very high temperature.

Fig. 4 represents the new laser chamber in referring to the developed patent (WO2019159088A1 [4]), and the laboratory-scale prototype used during the tests.

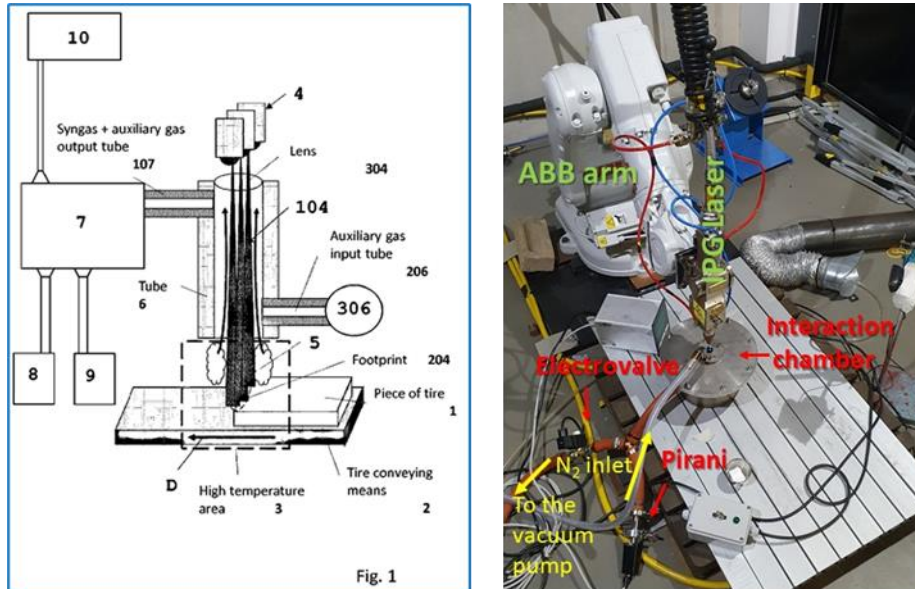


Fig. 4. The new laser chamber, patented scheme WO2019159088A1 [4] (left) and laboratory scale prototype (right).

3.3.2. Vacuum system

A further problem-solving session concerned the vacuum treatment system during gas measurement by chromatography. The problem in this case was to be able to remove gas via a syringe from a vacuum chamber. It was necessary to decrease the pressure delta between inside and outside to a level where it was possible to remove the gas using a syringe.

Instead of installing a system of valves and sensors connected to a multichannel data acquisition card, as normally used in university laboratories, a much more ideal method was suggested.

A solenoid valve had to be included between the pump and the chamber. This allows the system to hold a vacuum at the end of the process and maintain the gasses produced by the pyrolysis isolated. A Pirani gauge was inserted between the chamber and the solenoid valve.

With this configuration the vacuum level is always guaranteed during processing, but with the engine off, the inevitable pressure drops of the circuit that cannot keep the vacuum conditions for a long time are exploited, checking them for the time necessary to make the measurements.

Fig. 5 provides a representation of the functioning and shows the prototype of the vacuum management system.

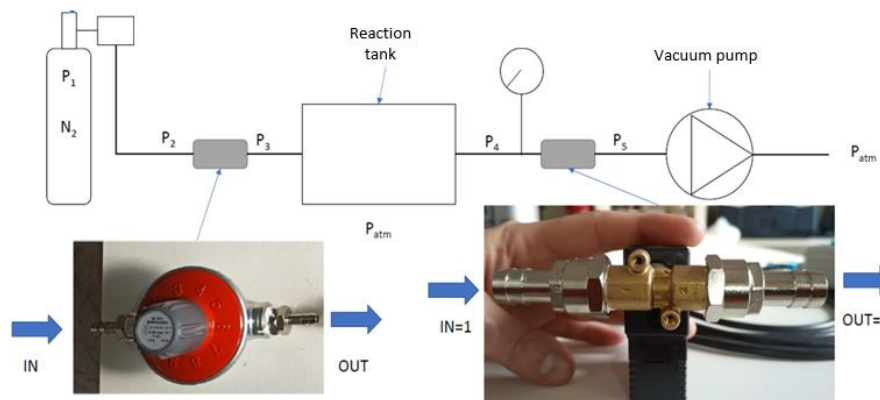


Fig. 5. Vacuum system.

5 Conclusions

The use of TRIZ has been the backbone of every activity of the presented project. Not only for the definition of the pioneering activity but also in the technical phases of prototyping. The purpose was to show how Triz can be used in a full project approach and not just to do problem solving or other specific activities. In the framework proposed for this case study, TRIZ fundamentals were crucial to design innovative solutions and for helping during testing phases but were also important to in-frame technical systems at the evolutionary level proved useful in setting up the study, which confirmed that laser pyrolysis could be the most promising solution.

The various experimental campaigns have given very encouraging results, not only with materials declared into the patents (tires and bitumen) but also with another waste materials recently tested.

The methodology also allowed us to create a narrative of the solution that will be critical for the next step, which consists in finding adequate funding for the realization of an industrial pilot.

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