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Innovative potential for improvements in pellet production: from the perspective of TRIZ and Axiomatic Design

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Abstract

Improving the efficiency of an energy pipeline industry is complex. Therefore, this article explores the production of pine wood pellets with the application of the Axiomatic Design (AD) and Inventive Problem-solving Theory (TRIZ) techniques, to develop solutions to increase the productive and environmental performance of a pellet industry of Brazil. The results indicate an increase in environmental energy efficiency, in the quality of pellets and possible trade-off situations, creating opportunities for future improvements. This aspect demonstrates that the solutions lead to the evolution of the technical system with potential for innovation.

Keywords: Axiomatic Design, Environmental Performance, Pellets, TRIZ.

1. Introduction

Forest biomass is considered a renewable energy source that indirectly takes advantage of sunlight, transforming it into carbohydrates through the biochemical processes of photosynthesis (Narodoslawsky, 2010). These carbohydrates are transformed into solid, liquid, and gaseous fuels to produce other types of energy, including electrical energy (Goldemberg, 2009). The total annual global consumption of biomass was estimated at 55 EJ, which represents 10.2% of all primary energy consumed in the world (Edenhofer et al., 2011). Of the total of 4 billion m^3 of wood consumed annually in the world, about 55% is used in the form of firewood or charcoal. Unfortunately, the energy efficiency of this form of biomass use is very low, with unused heat loss and high atmospheric emissions. Added to other polluting sources, these environmental effects have continued to expand, requiring improvement in the power energy system.

Accordingly, the European Council on the Environment adopted the "2030 Energy-Climate Framework", which has three objectives: to reduce greenhouse gas (GHG) emissions by 40% compared to 1990; placing renewable energies at the level of 27% of the European Union's energy consumption and improving energy efficiency by 30% (European Commission, 2020). A great example of sustainable energy products is wood pellets. The source is a type of granulated biofuel of lignocellulosic biomass with excellent energy potential (Li et al., 2013; Kaliyan & Morey, 2009). The raw material is derived from several vegetable sources, such as cereals straw, sugar cane (Nunes et al., 2013; Cortez et al., 2020) and mainly, forest residues, such as tree bark, sawdust. or wood shavings from by-products derived from the timber industries (Chen et al., 2015; Liu et al., 2013). For many years, wood chips have been the most used products in energy systems (Alizadeh & Lund, 2020), but in recent years, pellets have increased their field of application due to their high energy potential (Bioenergy Europe, 2019; European Commission, 2019, Stelle et al., 2011). The pellet production system is also an example of green manufacturing due to the use of raw materials and the process of recovering industrial waste. From this scenario, how could the efficiency of the energy pellet industry be increased in productive and environmental aspects? This problem was addressed in the form of applied research to generate deeper knowledge than a theoretical approach. An exploration in a real context has shown results that enable future applications to improve the efficiency of the industrial plant.

2. Industrial Sustainability in Closed-Loop Production of Pellet

In addition to the properties of pellets as renewable materials, other factors can be improved in the phase of their manufacture. A prominent example is the Closed-Loop Production (CLP) system. This manufacturing model makes it possible to recover and insert by-products of the raw material in manufacturing, to reduce the consumption of materials and disposals, and to act systemically in operations and industrial costs (Gu et al., 2016). The CLP system increases the energy and productive efficiency of the manufacturing plant. But this model does not have wide application in industrial areas. The studies also highlight the importance of increasing the energy management of a factory from the stage of energy supply or feedback, to potentiate industrialization (Alizadeh & Lund, 2020; EUROPEAN COMMISSION, 2019; IEA, 2019). By integrating production and energy concepts in the same plant, there are specific variables that make the control and optimization of this type of industry more complex. Within this context, this paper proposes to identify and evaluate solutions that allow to increase the productive and environmental performance of CLP to increase the values of industrial sustainability. The complexity of this subject requires a theoretical approach to the conceptual foundation to identify conditions for improvement. The application of the proposal under operating conditions can define the model.

The pellet production system represents the context described. **Figure** 1 shows a typical pellet production chai, and considers the references of the database called "Industrial wood waste pelletizing, wood pellets A1", which considers industrial waste processing in accordance with DIN EN 14961-2 (2010) European Pellet Council (EPC, 2015). The power plant phase represents of Linear Production (PL) of the pellets system, and input/output flow in the first stage, and goods to the warehouse in the last phase.

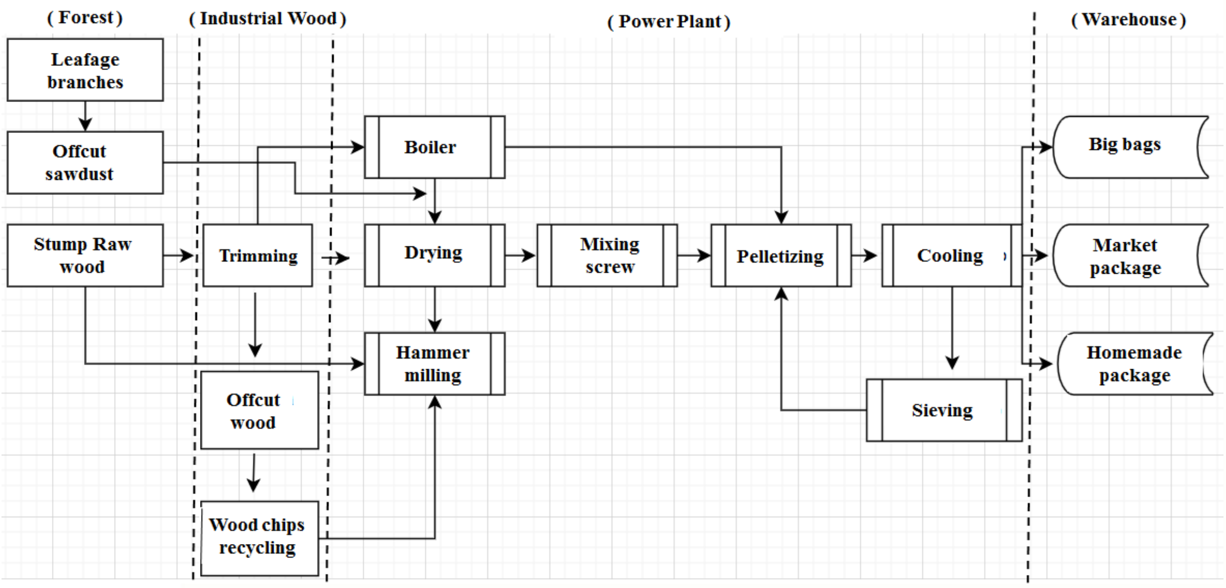


Fig 1. Wood pellet production chain.

2.1 Axiomatic Design and TRIZ applied in a pellet production system

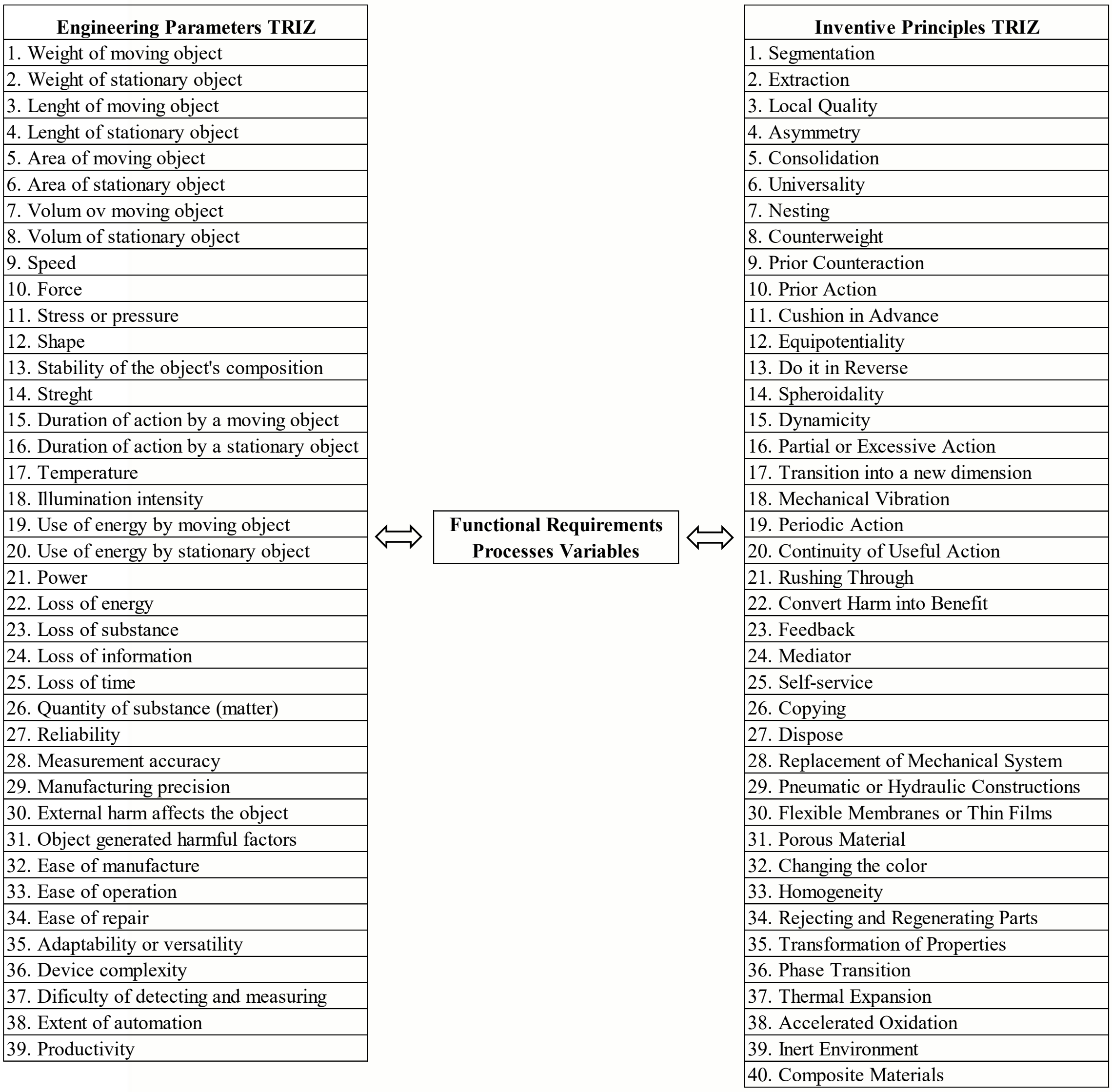
Some industrial systems for the generation of energy products have an advanced technological level. The CLP model is an example because it reduces environmental effects in the primary phase (raw material) and also in the manufacturing stage by reducing the volume of by-products. Developing improvements to increase production efficiency is very important because it does not require high investments in new projects (greenfield plant), which requires large infrastructure involved and generates process stoppages for the implementation of changes. On the other hand, the improvements developed by remodeling variables of the existing technology, promote the condition of evolution to the industrial system itself, using its resources and process parameters to increase its efficiency. Considering this context, the TRIZ methodology was applied, using the system's PE for evaluation and generation of PI for improvements. In connection with this tool, the concepts of AD were applied, which makes interactions between system operators to improve the structure of the solution for processes and their functions.

For the detailed evaluation of each process, the Axiomatic Design (AD) was applied, which operates as a tool for systematic analysis of complex systems. Initially, AD axioms were considered in manufacturing systems (Suh, 2001) to structure the parameters and information about the product system. Axioms assume the relationship between domains and design elements in the duality between User and User Requirement (RU); Functional and functional requirement (RF); Physical and Design Parameter (PP) and Process and Process Variable (VP) (Harutunian et al., 1996). User Requirements (RUs) present the needs and expectations of users during the product life cycle, so they interact with Functional Requirements (RFs) to form the elementary structure of the basic requirements of the project. The Design Parameters (PPs) are the elements of the design solution in the physical domain, being associated with the Process Variables (VPs) that characterize the manufacturing methods and processes and meet the specified PP, being also established independently of the solution. The axiomatic approach is based on the interaction between RF and physical attributes. Thus, RF is achieved by the interaction between how to develop solutions and conflict or contradictory situations, which are applied by the TRIZ method. However, using this procedure is complex because it involves detailed evaluation in splitting stages of conflicting characteristics in time, space, and the system, and administrative, technical, and physical contradictions (Altshuller, 1998). These forms of contradictions structure a context of ideality and principles of split to develop solutions in the TRIZ model. The separation procedure delimits the physical aspects, the functional requirements and the contradictions to be eliminated, which at TRIZ are worked on through the evolution of the technical system that also involves environmental variables (Altshuller, 1989). For this characteristic, TRIZ's ARIZ 85A technique, analyzes sections to understand the whole, operating by cyclical and continuous assessments to explore the relationships and their hierarchies, as provided by the AD. This process involves studying analogous or non-analogous projects and heuristics in order to develop more creative and less complex ideas (Kwon, Lee & Kim, 2015). TRIZ enables a trend of multidisciplinary evolution, systematically exploring technological evolution for the generation of new solutions (Althsuller, 1999). In this sense, the correlation between AD and TRIZ is presented in table 1:

Table 1. Relationship AD and TRIZ.

Domain specifications		TRIZ			
DC	Customers	OS	Systems operators	Heuristics	
↑ RF	Functional (Functional Requirements)	↑ PE	Engineering Parameters	↓	
PP	Physical (Parameter Project)	ST	Technical Systems	PI	Inventive principles
↓ VP	Process (Processes Variables)	↓ PE	Engineering Parameters	↑	

The table shows the AD domains for the operators of the analysis system and the variables that lead to the development of heuristics. This logic is consistent with the chained and systematic approach to the development of solutions generated from the Altshuller PI (1998), the Savransky Principles (2003), and the Combined Principles proposed by Mann et al. (2010). Heuristics based on evidence of utility in projects help to develop solutions (Daly et al., 2012; Tessari & De Carvalho, 2015) according to functions and substances that exist or are absent, to develop the resolution of problems. In this context, the connection between TRIZ's PE and PI with the AA's RF and VP is shown in **Figure 2:**



Engineering Parameters TRIZ
1. Weight of moving object
2. Weight of stationary object
3. Lenght of moving object
4. Lenght of stationary object
5. Area of moving object
6. Area of stationary object
7. Volum ov moving object
8. Volum of stationary object
9. Speed
10. Force
11. Stress or pressure
12. Shape
13. Stability of the object's composition
14. Streght
15. Duration of action by a moving object
16. Duration of action by a stationary object
17. Temperature
18. Illumination intensity
19. Use of energy by moving object
20. Use of energy by stationary object
21. Power
22. Loss of energy
23. Loss of substance
24. Loss of information
25. Loss of time
26. Quantity of substance (matter)
27. Reliability
28. Measurement accuracy
29. Manufacturing precision
30. External harm affects the object
31. Object generated harmful factors
32. Ease of manufacture
33. Ease of operation
34. Ease of repair
35. Adaptability or versatility
36. Device complexity
37. Dificulty of detecting and measuring
38. Extent of automation
39. Productivity

⟺ **Functional Requirements Processes Variables** ⟺

Inventive Principles TRIZ
1. Segmentation
2. Extraction
3. Local Quality
4. Asymmetry
5. Consolidation
6. Universality
7. Nesting
8. Counterweight
9. Prior Counteraction
10. Prior Action
11. Cushion in Advance
12. Equipotentiality
13. Do it in Reverse
14. Spheroidality
15. Dynamicity
16. Partial or Excessive Action
17. Transition into a new dimension
18. Mechanical Vibration
19. Periodic Action
20. Continuity of Useful Action
21. Rushing Through
22. Convert Harm into Benefit
23. Feedback
24. Mediator
25. Self-service
26. Copying
27. Dispose
28. Replacement of Mechanical System
29. Pneumatic or Hydraulic Constructions
30. Flexible Membranes or Thin Films
31. Porous Material
32. Changing the color
33. Homogeneity
34. Rejecting and Regenerating Parts
35. Transformation of Properties
36. Phase Transition
37. Thermal Expansion
38. Accelerated Oxidation
39. Inert Environment
40. Composite Materials

Fig 2. TRIZ's PE and PI relationship

3. Methodology

The study has an exploratory approach applied to a real experience, to generate a more comprehensive and rodusta investigation of an industrial context. In this way, this work is an applied research that was carried out in the energy products industry. The methodological organization was based on a theoretical basis to demonstrate tools for approaching and recognizing the object of solid study. In the next sections of research, the context and its variables were explored for the application and evaluation of its results. This methodological procedure is designed with the TRIZ technique because it evaluates a condition (problem situation) in order to develop improvements, in a structured and systematic way. Being an applied research, the industrial system is the object of exploration, and TRIZ and AD are the instrumental methods for generating improvements that will be evaluated in the stages of results and conclusion. In summary, the methodological scope associates the flow object of investigation in the following sections of the paper, material, and methods => results => discussions conclusion.

4. Material and Methods

4.1 Evaluation of the pellet production system

The industrial plant under analysis is located in the south of Brazil, and being one of the main exporters to the European market. The production meets the international standards of the ENplus A1 standard, which certifies high-quality standards throughout the pellet production chain. The production system can adapt according to the technological level and the quality standard of the product to be produced. Brazilian companies adapt their industrialization process to the European standards of the European Committee for Standardization (NREL, 2010) in order to serve the international market with the DIN and ISO quality standards in the ENplus® standard. The pellets are produced from pine wood residues in accordance with the ENplus® standard (EPC, 2015) presented in table 2:

Table 2. ENplus® data.

Parameter	Data reference (units)
Diameter	6 ± 1 ou 8 ± 1mm
Length	3,15 < L = 40mm
Umidity	10% moisture
Ash	0,7% of dry mass
Mechanical durability	98,0 % moisture
Temperature	< 40ºC
Higher heating value	> 4,6 kWh/kg (≥ 16,5 MJ/kg)
Bulk Density (BD)	600 ≤ BD ≤ 750 kg/m^3

The evaluation productive system is delimited from "gate to gate", considering only the processes of industrialization of pellets, as shown in **Figure 3**:

The input flow considers the raw material wood residues, energy in the form of electricity, and other substances used in the industrialization process. The outflow is waste or by-products generated. Emissions are also elements of outputs, receiving special observation due to the characteristics of production. As the analysis system considers closed-loop production, emissions from primary processes and production reuse processes are considered. The information data was collected from the Bioenergy Life Cycle Inventory (ICV) of the Swiss Center Ecoinvent, version 2.0 (2007) and technical data on substances from the Pellets Fuel Institute (PFI) (NREL, 2012), from the Bioenergy Europe statistical report on pellets (2019), the European Pellet Council (EPC, 2015), the Handbook on pellets (Obernberger & Thek, 2010) to be able to apply in the analysis considerations.

The general description of the domains in AD om productive system is presented as:

- RF in the functions that the product must fulfill;
- PP in the product design within the specifications of the ENPlus standard padronization;
- VP of production process parameters.

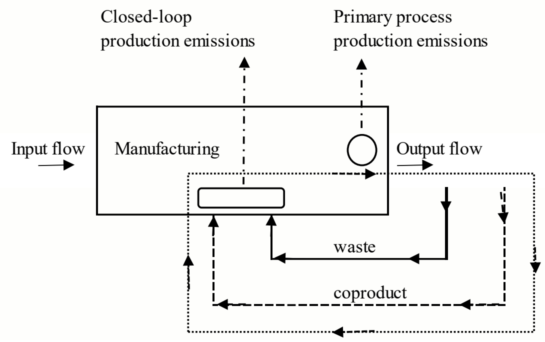


Fig 3. Productive system.

The specification of domains originating in:

The PP related to the physical parameters of the product design with its characteristics and properties regulated in the ENPlus standards and in the Handbook on pellets "The production and thermal use of biomass pellets" (Obernberger & Thek, 2010).

For the parameter RF, they refer to the properties and functions of the product and is represented in calorific value, mechanical resistance, smoke emission, odor emission, waste emission, dimensions (length, diameter, and mass), and appearance (shape and colors). These technical data represent the factors that characterize the RF of substances.

The VP comprises the parameters used in industrial devices and processes and refers to the operations of preparing the mixture, grinding, drying, pelletizing, cooling, and dimensional analysis of the product and packaging. These data represent the specific factors of the PV. From this information, with the outline of the factors that associate the RF or VP, the corresponding PIs are identified, forming the correlation matrix between AD and TRIZ to identify the generic solution associated with each element of analysis, shown in **Table 3**:

Table 3. AD and TRIZ correlation and generic solutions

Domaine	RF or VP description	Factors	PI	Description	Generic Solution (based on industrial process data)
RF	Net calorif value	All substances	5. Consolidation	Amount of blend components	"Poka-Yoke" system to recipe of components
RF	Smoke emissions (-)	Wood	(all substances)	Homogeneous blend of substances	Mixer machine with variable and regenerative cycles of operation
RF	Odor emissions (-)	Sawdust		Recovery emissions	Recovery particulate substances (filter, burn, remanufacturing)
RF	Waste emissions (-)	Fluid			
RF	Dimension (lenght/diameter/weight)	Water		Dimensional and profile evaluation	Comparision with quality standard
RF	Profile (shape and color)				
RF	Net calorif value	Substances	5. Consolidation	Amount of blend components	Mixer machine with variable and regenerative operating cycles
RF	Mechanical durability	Blended	33. Homogeneity	Density bulk	Increase pressing force
RF	Profile (shape and color)	Homogeneity		Homogeneus blend of substances	Increase potential for compaction of substances
RF	Net calorif value	Moisture	29. Pneumatic or Hydraulic Constructions	Mixing process	Mixer machine with variable and regenerative operating cycles
RF	Mechanical durability	Moisture		Density bulk	Increase pressing force
				Drying	Increase drying (hot and cool matching (contradiction))
RF	Mechanical durability	Durability	5. Consolidation	Homogeneus blend of substances	Mixer machine with variable and regenerative operating cycles
RF	Dimension (lenght/diameter/weight)	Dimension	36. Phase Transition		Increase drying (hot and cool matching (contradiction))
RF	Profile (shape and color)	Aspect	33. Homogeneity		
RF	Profile (shape and color)	Color	32. Changing the color	Homogeneus blend of substances	Mixer machine with variable and regenerative operating cycles
					Standardized setup (apply of automation of processes)
VP	Setup	Wood	5. Consolidation	Homogeneus blend of substances	Mixer machine with variable and regenerative operating cycles
		Sawdust	(all substances)		Standardized setup (apply of automation of processes)
		Fluid			
		Water			
		Moisture	35. Physical or chemical transformation	Drying	Increase drying (hot and cool matching (contradiction))
		Dimension	17. Transition into a new dimension	Measure and weigh blend of substances	"Poka-Yoke" system to recipe of components
		Homogeneity	33. Homogeneity	Homogeneus blend of substances	Mixer machine with variable and regenerative operating cycles
VP	Milling	Pressure	36. Phase Transition	Process parameters	Standardized setup (apply of automation of processes)
		Temperature	36. Phase Transition	Process parameters	Standardized setup (apply of automation of processes)
		Homogeneity	33. Homogeneity	Homogeneus blend of substances	Mixer machine with variable and regenerative operating cycles
VP	Drying	Temperature	36. Phase Transition	Process parameters	Standardized setup (apply of automation of processes)
		Moisture	35. Physical or chemical transformation	Drying	Increase drying (hot and cool matching (contradiction))
VP	Pelletization	Pressure	36. Phase Transition	Process parameters	Standardized setup (apply of automation of processes)
		Temperature	36. Phase Transition	Process parameters	Standardized setup (apply of automation of processes)
VP	Cooling	Temperature	36. Phase Transition	Process parameters	Standardized setup (apply of automation of processes)
		Moisture	35. Physical or chemical transformation	Drying	Increase drying (hot and cool matching (contradiction))
VP	Dimensional evaluation (fines)	Dimension	17. Transition into a new dimension	Fines recovery	Closed-loop pelletizing
VP	Packing	Dimension	17. Transition into a new dimension	Check the weight of the packages	"Poka-Yoke" system to recipe of components

To understand the potential of the solutions presented, the classification proposed by Altshuller (1998) from TRIZ is considered, with a score that qualifies solutions according to the level of complexity, creativity, and innovation (Navas et al., 2015), which is demonstrated in the following taxonomy of solutions presented in **Table 4**:

Table 4. TRIZ level of generical solutions.

Generic Solution	Level
"Poka-Yoke" system to recipe of components	2
Mixer machine with variable and regenerative operating cycles	3
Increase drying (hot and cool matching (contradiction))	2
Standardized setup (apply of automation of processes)	2
Closed-loop pelletizing	3
Increase pressing force	1
Recovery particulate substances (filter, burn, remanufacturing)	3
Comparising with quality standard	1

Engineering Parameters (PE)	Contradictions (C)	Inventive Principles (PI)
11. Stress or pressure	Pressure, temperature, shape, energy Restrictive factors	1, 2, 19, 35
17. Temperature	Pressure, temperature, shape, energy Restrictive factors	15, 19, 35, 36
19. Use of energy by moving object	Blend stability Complexity of control	3, 10, 13, 36
20. Use of energy by stationary object	Blend stability Quantity of substance	35
26. Quantity of substance	Loss of energy or substance Reliability	5, 10, 23, 35
32. Ease of manufacture	Quantity of substance, maintenance Reability	19
38. Extent of automation	Adaptability, maintenance	28

Table 5. Inventive Principles.

The classification also seeks to stimulate the development of more complete and innovative solutions, in order to achieve the evolution of the system, that is, to seek ideality, which is one of the most important principles of TRIZ (Zlotin et al., 2011). Looking at **Table 2**, there is a greater concentration in levels 2 and 3, therefore, there is an opportunity to develop level 4 solutions, that is, those that are developed from the application of new scientific concepts and are limited to about only 4% of the contingent of solutions generated (Navas et al., 2015). Applying the contradiction matrix, which relates the PE with the contradictory parameters, the following PI are identified in **Table 5:**

From the identification of the PI, the description of the improvements to be applied in the processes is presented:

PI 1: Segmentation

Segmentation suggests a separate analysis of the components of the pellet-forming mixture. The objective is to find out what is the level of emissions of each of the components, to identify which component has the greatest contribution. From this data, investigate which material could be replaced with the same energy potential. The materials are: forest waste; green sawdust and water.

PI 2: Extraction

PI 2 is related to PI 1. Segmentation analyzes the influence of each material and PI 2 acts to remove or reduce the composition of the impacting substance. Observing the composition of the pellet materials (table 5), A1 class it is recommended to reduce to a lower rate than the material composition, main pollutants substances, suggested by the standard are azote: ≤ 0,3 (%), chlorine: ≤ 0,02 (%) and ash: ≤ 0,7 (%). Data presented in table 6:

Table 6. Pellets compositions ENplus Standard.

Substances - EnPlus Classes		**A1**	**A2**	**A3**
Moisture	%	≤ 10	≤ 10	≤ 10
Ash	%	≤ 0.7	≤ 1.5	≤ 3.0
Bulk Density	kg/ m^3	≥ 600	≥ 600	≥ 600
Mechanical Durability	%	≥ 97.5	≥ 97,5	≥ 96.5
Net Calorific Value	MJ/kg	16.5 a 19	16.3 a 19	16 a 19
Fines	%	≤ 1	≤ 1	≤ 1
Sulfur	%	≤ 0.03	≤ 0.03	≤ 0.04
Azote	%	≤ 0.3	≤ 0.5	≤ 1
Chlorine	%	≤ 0.02	≤ 0.02	≤ 0.03
Arsenic	mg/kg	≤ 1	≤ 1	≤ 1
Cadmium	mg/kg	≤ 0.5	≤ 0.5	≤ 0.5
Chromium	mg/kg	≤ 10	≤ 10	≤ 10
Copper	mg/kg	≤ 10	≤ 10	≤ 10
Lead	mg/kg	≤ 10	≤ 10	≤ 10
Mercury	mg/kg	≤ 0.05	≤ 0.05	≤ 0.05
Nickel	mg/kg	≤ 10	≤ 10	≤ 10
Zinc	mg/kg	≤ 100	≤ 100	≤ 100

PI 3: Quality Assurance

The quality of the pellet product and its production process is related to the lower environmental effect generated. Starting from the substances responsible for the discharges identified in PI 1 and 2, the categories of environmental impact classified in the dimension "pollution" are identified according to the standard ISO / TR14047 (US EPA, 2006). The pollution group generates global warming and the depletion of the ozone layer by the CH4, NH3 and CO2 emissions that occur in the processes, under conditions of direct potential impact “+” and indirect potential impact “(+)” is presented in **table 7**:

PI 5: Combination

This PI suggests the combination of operations in time and space with other industrial processes. This solution increases production efficiency by taking advantage of the system's own unused energy sources. It is about identifying passive energy generating processes, in kinetic, mechanical or thermodynamic form. The installation of an energy capture and conversion device is the solution to combine operational efficiency with sustainability. The use of these sources of cogeneration can replace part of the consumption of the original energy

Table 7. LCA impact categories

Categories of impact	General areas of protection Natural Resources	 Human Health	 Environmental Health
a) Depletion of resources			
Abiotic resources	+		
Biotic resources	+		
b) Pollution			
Global warning		(+)	+
Stratospheric ozone depletion		(+)	(+)
Photo-oxidant formation		+	+
Acidification		(+)	+
Eutrophication			+
Human toxicity		+	
Ecotoxicity		(+)	+
c) Damage to ecosystem			
Land use			+

unit and reduce the emissions generated, mainly, derived from electricity. The main sources for conversion are mass; heating specific value; power; speed; rotative devices (turbines) or linear motion equipment. In all situations, it is necessary to identify the conversion coefficient to apply to the energy combination system.

PI 10: Prior action

This PI can be applied in two dimensions. A simplified proposal is linked to the "End of Pipe" principle of cleaner production (Kong et al., 2013), with the introduction of filters in the system to avoid discharges and environmental effects. The installation can be applied in the following ways: filters after the process (retention of atmospheric emissions); and filters in the replenishment flow of material recovered from the process.

Another form of prior action would be the specification of standardized methods and processes for the efficient preparation of the mixture, generating a balanced composition of components as the materials are presented in relation to their granulometry or moisture so that the mixture's homogenization or substance addition is increased binder.

PI 13: Inversion

The process of reintroducing materials for reprocessing characterizes the inversion of the material flow because the outlets become the inputs in the process. This form of operation designates the production of closed-loop production, reducing the consumption of primary resources in its material design and also of energy. Recovery involves co-products or materials that have not reached specified quality standards and avoids unnecessary disposal, thus minimizing discharges and emissions during pellet industrialization.

PI 15: Dynamics

The application of PI 15 can be performed through a new specification of the material grinding process, seeking to optimize the use of the primary resource. Right after the grinding process, the materials are inspected using a sieve with the smallest allowed specification of the diameter of the particles to generate dynamism in the use of the materials. This procedure will streamline the frequency of selection of materials and also make better use of the raw material. The processes use mesh for the 8 mm diameter of the particles.

Another possibility would be to recalibrate the operation of the metering valve of the pre-pelletizing mixture, so that the matrix filling is adequate and equivalent to the level of inlet pressure of the pelletizer, as the process is responsible for the fusion of lignin and the union of wood.

PI 19: Periodic action

The variables acting on this inventive solution are temperature and pressure. These parameters are fundamental for productive efficiency in quality and productivity. Installing sensors for remote and periodic control of production conditions enables continuous monitoring of operations. The monitoring will serve to reduce the loss of energy load and keep the process stabilized. Supervisory production systems are complete and automated devices to control and act on production processes.

PI 23: Feedback

Reusing input waste can mitigate waste and pollution. This PI seeks to raise the level of environmental management in accordance with ISO 14000 (ABNT: ISO 14000). The solution is to recover the fines of pellets with a dimension smaller than specified by the standard, reintroducing in the pelletization process what characterizes the feedback principle. The recovery goes through a period of partial reserve of the material and later replenishment. It is important to highlight the possible interference on the property of lignin in agglutinating the material, due to its secondary use, after the material undergoes a mechanical process and at an elevated temperature. The expansion of the pellet by changing the temperature must also be checked, which must be readjusted to homogenize the mixture. The standard ENplus A1 specifies fines content less than 1% (EPC, 2015) of the pellet mass, expressed by the amount of powder present in the sample related to the initial mass (DIN EN 15210-1, 2010) or less than 3, 15 mm (ISO 3310-2: 2010). The granulometric classification sieve must be used to separate the 3.15 mm grains to avoid the destination of very small particles and to generate more ash in the boilers, that is, to avoid the emission of particles in the atmosphere.

PI 28: Replacement of Mechanical Devices

This PI is related to PI 19, which suggests the implementation of automated systems for monitoring and controlling production by supervisory systems. The automated means replace mechanical devices for parameterizing process data, such as pressure and temperature settings. This inventive solution allows greater accuracy in regulation data, real-time monitoring, and remote action if necessary.

PI 35: Change of Physical or Chemical State and PI 36: Phase Change

The change in state is associated with the state of aggregation, concentration, or consistency of the condition of the material. In this sense, this PI is associated with the way to improve the results of productivity and sustainability of production. The first case is related to improving the consistency of the mixture with the introduction of additives for this purpose. Lignin is the main substance responsible for increasing the consistency and energetic power of the pellet, but this substance is already present in the primary raw material. An alternative is to apply the starches derived from corn, potatoes, rice, wheat, or manioc because they are organic derivatives with the presence of natural oil that acts as a lubricant for the pressing matrix (Unpinit et al. 2015). However, it is necessary to perform heating of the additive with water vapor to occur the gelatinization reaction, which consists of a chemical reaction so that the starch granules adhere to the components of the mixture. Another inventive solution would be to cool the pellets by thermal exchange for the mixture. After the pelletization process, the pellets are at a temperature close to 90oC and require cooling. This calorie would be transmitted, through induction, to the mixture, for example, the incorporation of additives.

4.2 Trends of Evolution

For Altshuller (1998) the trends in the evolution of technical systems allow to increase the predictability of the technology evolution process. In other words, the analysis of the technological standards of existing products helps to predict the next steps of evolution and to make strategic decisions in the development of other projects. Therefore Altshuller (1998) established eight trends for the evolution of technical systems (Lavengin, 2013):

1. Technology follows a cycle of birth, growth, maturity, and decline;
2. Increasing ideality;
3. Unbalanced development of subsystems, resulting in contradictions;
4. Increased dynamism and controllability;
5. Increasing complexity, followed by simplicity;
6. Joining and splitting system components;
7. Transition from microsystems to macrosystems using energy fields to improve performance and control;
8. Reducing human involvement on devices with increasing automation.

According to the principles of TRIZ systems evolve to increase ideality, being directly proportional to positive attributes and inversely proportional to negative factors and costs (Nakagawa, 2001). In addition to the eight evolution trends mentioned, there are twenty other evolution patterns, called Property Spectrum (SP) that show the trajectory of properties that are altered or transformed when passing from one product to another (Mann et al. 2010): 1. State; 2. Heartbeat; 3. Fragmentation; 4. Surface; 5. Porosity; 6. Automation; 7. Form; 8. Transparency; 9. Color; 10. Coordination; 11. Flexibility; 12. Direction; 13. Integration; 14. Opposites; 15. Market; 16. Information; 17. Symmetry; 18. Fibers; 19. From liquid to spray; 20. From liquid to foam. Following this vector of systematic improvement, Mann (2002) listed 31 Trends of Evolution (ET), presented in **Table** 8 to demonstrate the evolutionary potential of each of the trends:

Table 8. 31 Evolution Trends (31 TE) (MANN, 2002)

Evolutionary trend		Evolutionary potential
1	Smart materials	1.1 Passive material 1.2 Adaptable material (one-way) 1.3 Adaptable material (two-way) 1.4 Adaptable material (full)
2	Space segmentation	2.1 Solid monolithic 2.2 Hollow structure 2.3 Multiple hollow structure 2.4 Porous structure 2.5 Porous structure with active additives
3	Surface segmentation	3.1 Smooth surface 3.2 Surface with rib protrusions 3.3 3D roughened surface 3.4 Roughened surface + active pores
4	Object segmentation	4.1 Solid monolithic 4.2 Segmented solid 4.3 Particulate solid 4.4 Fluid 4.5 Segmented fluid 4.6 Gas 4.7 Plasma 4.8 Field 4.9 Vacuum
5	Evolution macro to nano scale (space)	5.1 Continuous (at all levels): 10^2 => 10^1 => 10^0 => 10^{-1} => 10^{-2} => 10^{-3} = 10^{-4} => 10^{-5} ...
6	Webs and fibres	6.1 Homogeneos sheet structure 6.2 2D surface regular mesh structure 6.3 3D fibers alignment according load conditions 6.4 Addition of active elements
7	Decreasing density	7.1 Continuous (at all levels): 10^2 => 10^1 => 10^0 => 10^{-1} => 10^{-2} => 10^{-3} = 10^{-4} => 10^{-5} ...
8	Increasing asymmetry (to match external asymmetries)	8.1 Symmetrical system 8.2 Partial asymmetry 8.3 Matched asymmetry
9	Boundary breakdown	9.1 Many boundaries 9.2 Few boundaries 9.3 No boundaries
10	Geometric evolution (linear)	10.1 Point 10.2 1D line 10.3 2D plane 10.4 3D surface
11	Geometric evolution (volumetric)	11.1 Planar structure 11.2 2D structure 11.3 Axisymmetric structure 11.4 3D structure
12	Dinamization	12.1 Immobile system 12.2 Jointed system 12.3Full flexible system 12.4 Pneumatic system 12.5 Modular system (field)
13	Action coordination	13.1 Non coordinated action 13.2 Partially coordinated action 13.3 Fully coordinated action 13.4 Different actions during intervals
14	Rhythm coordination	14.1 Continuos actions 14.2 Periodic action 14.3 Use of resonance 14.4 Travelling wave
15	No linearities (matching to external)	15.1 Linear consideration of system 15.2 Partial accouting of non linearities 15.3 Full accommodation of non linearities
16	Mono/Bi/Poly (similar)	16.1 Mono-system 16.2 Bi-system 16.3 Tri-system 16.4 Poly-system
17	Mono/Bi/Poli (various)	17.1 Mono-system 17.2 Bi-system 17.3 Tri-system 17.4 Poly-system
18	Mono/Bi/Poli (increasing diferences)	18.1 Similar components 18.2 Components with biased characteristics 18.3 Component plus negative component 18.4 Different components

19	Reduced damping	19.1 Heavy damping 19.2 Critical damping 19.3 Light damping 19.4 Un damped
20	Increased use of senses	20.1 1 sense 20.2 2 senses 20.3 3 senses 20.4 senses 20.5 5 senses
21	Increasing color use	21.1 No use of color (monochromatic) 21.2 Multicolor 21.3 Visible spectro 21.4 Full spectro
22	Increasing transparency (seamless)	22.1 Opaque construction 22.2 Partially transparent 22.3 Transparent 22.4 Active transparente elements
23	Customer purchase focus	23.1 Performance 23.2 Reliability 23.3 Convenience 23.4 Price
24	Market evolution	24.1 Commodity 24.2 Product 24.3 Services 24.4 Experience 24.5 Transformation
25	Design point (milestone)	25.1 Design optimized for single operation 25.2 Design optimized for two operations 25.3 Design optimized for several discrete operations 25.4 Design reoptimized continuosly
26	Degrees of freedom (DF)	26.1 1 DF 26.2 2 DF 26.3 3 DF 26.4 4 DF 26.5 5 DF 26.6 6 DF
27	Trimming	27.1 Complex system 27.2 Elimination of no key components 27.3 Elimination of non-key sub-systems 27.4 Trimmed system
28	Controllability	28.1 Direct control action 28.2 Action through intermediar 28.3 Addition of feedback 28.4 Intelligent feedback
29	Reducing human involvement	29.1 Human 29.2 Human + tools 29.3 Human + powered tools + 29.4 Human + semi automated tools 29.5 Human + automated tools 29.6 Automated tools
30	Design methodology	30.1 Cut and try 30.2 Steady state design 30.3 Transient effects included 30.4 Slow degradation effects included 30.5 Cross coupling effects 30.6 Design for murphy
31	Reducing number of energy conversions (zero goal)	31.1 3 energy conversions 31.2 2 energy conversions 30.3 1 energy conversion 30.4 No energy conversion

Correlating the 8 Evolution Trends (8 TE) with the 20 Property Spectrum (20 SP) and the 31 Evolution Trends (31 TE), it is possible to verify the innovation potential that may be provided by the evolution process of the technical system with the PI, is presented in table 9:

Table 9. 31 Mapping of technical system evolution.

8 TE	PI	20 EP	PI	31 TE	PI
1. Technology follows a birth cycle, growth, maturity and decline		1. Physical matter	35	1. Smart materials	
2. Continuous growth of ideality	15 , 19 , 23	2. Pulsation	3	2. Space segmentation	5
3. Inequality in the development of sub-systems, resulting in contradictions	13 , 23	3. Fragmentation	1 , 2	3. Surface segmentation	
4. Increasing dynamism and controllability	15	4. Surface		4. Object segmentation	1
5. Increasing complexity, followed by simplicity	5 , 10	5. Porosity	5	5. Evolution macro to nano scale	
6. Integrating and separating parts of system	1, 2	6. Automation	28	6. Webs and fibres	
7. Transition from microsystems to macrosystems using energy fields to improve performance	1 , 2 , 35 , 36	7. Shape		7. Decreasing density	5
8. Reduction of human involvement and increasing automation	19 , 28	8. Transparency		8. Increasing asymmetry (matching to external)	10
		9. Color		9. Boundary breakdown	
		10. Controllability	10	10. Geometric evolution (linear)	
		11. Flexibility	3 , 15	11. Geometric evolution (volumetric)	3
		12. Senses	19 , 23	12. Dinamization	15
		13. Integration		13. Action coordination	13
		14. Opposites	2 , 13 , 35	14. Rhythm coordination	10 , 19
		15. Market		15. No linearities (matching to external)	
		16. Information		16. Mono/Bi/Poly (similar)	
		17. Symmetry	36	17. Mono-bi-poli (various)	23
		18. Fibres		18. Mono/Bi/Poli (increasing diferences)	
		19. From liquid to spray		19. Reduced damping	
		20. From liquid to foam		20. Increased use of senses	
				21.Increasing color use	
				22. Increasing transparency	
				23. Customer purchase focus	
				24. Market evolution	
				25. Design point (milestone)	
				26. Degrees of freedom (DF)	
				27. Trimming	2
				28. Controllability	23
				29. Reducing human involvement	28
				30. Design methodology	
				31. Reducing number of energy conversions	35 , 36

Analyzing the spreadsheet, it is observed that the highest frequency of occurrence of the following evolution trends by evolutionary models are:

- 8 TE: 4 times TE 2 (Ideality) and TE 7 (Transition from microsystems to macrosystems);
- 20 SP: 3 times the EP 11 (Flexibility);
- 31 TE: 2 times the TE 14 (Coordination of rhythms) and TE 31 (Reduction of energy use).

5. Discussions and Conclusion

The results show that there are no correlations with the same evolution trends, however, there is a multidisciplinary transformation involving the evolution of the technical system. The changes must start from modifications of specific points to project to larger contexts (micro to macro system), bringing greater capacity for adaptations to processes (flexibility and pace) to minimize industrial interferences and, mainly, environmental effects with greater economy of energy. This set of transformations seeks ideality, which is one of the fundamental principles of TRIZ. Regarding the technical aspects, it is possible that some of the inventive solutions created have specific characteristics, and may generate limitations in other processes (trade-off), according to each type of PI applied. For example, studies indicate that the introduction of waste, related to PI 23, can improve the density of the pellet, but does not increase its mechanical hardness, and may even increase the level of emissions if the reuse content exceeds more than 50% of reused waste (Miranda et al., 2012; Nunes, 2013).

The PI 35 and PI 36 solutions aimed at the control and calibration of pressure and temperature parameters are determining factors for the production of pellets with quality standards. However, it is important to check the notes in the "Handbook of pellets" (Obernberger & Thek, 2004) which demonstrates the interference of parameters on solid biofuels, in terms of apparent density, moisture and ash contents, calorific value, abrasion, the use of starch additives, the composition of different chemical elements and the presence of heavy metals. The amount of ash is related to the chemical composition of the pellets, which have interference from PI 35 and 36 as well. If there is a high content of ash emission, there will be nitrogen, chlorine, and potassium, and these chemical residues are responsible for the problems of corrosion and accumulation in the flue gas elimination pipes of the process equipment. In this case, the installation of filters reduces the emission of pollutants, as indicated in PI 10. Researches show that pellets derived from eucalyptus wood have an ash content of 0.93%, while pine pellets have an ash content ranging between 0.33 % up to 0.59% (Garcia et al., 2016). Therefore, solutions directed by PI 15 and PI 19 must have control as to the type of material to be replaced.

The moisture content of the lignocellulosic material at the entrance of the pelletizing process directly influences the amount of energy required for the machines. The higher moisture content reduces the energy required but produces pellets with lower density and durability. Moisture decreases friction when the material passes through the pelletizing die holes and also at the back pressure. On the other hand, low moisture content increases the back pressure, resulting in high bulk density and higher energy consumption of the press. The optimum moisture content for the raw material is determined between 10% to 15%, depending on the type of material, as well as the amount of energy consumed during the pelletization process, which should not exceed 4% of the energy contained in the material raw material (Garcia-Maraver & Carpio, 2015). These factors are important for the closed-loop production process due to specific characteristics of the recovery of by-products, mentioned in PI 23. The temperature of the raw material used influences the performance of the production process, therefore, they can be controlled by PI19 and PI 28 The higher the temperature at the entrance of the process, the better result will be achieved in the pressing, resulting in a biofuel with higher density and durability, and less lower energy consumption (Nielsen et al., 2009).

Opportunities for future work

One of the evolutions in pellet production can be made by the torrefaction processes (Pirraglia et al., 2012; SCI, 2018). This process presents level 4 of TRIZ, as the solution is generated from new scientific concepts. The torrefaction is a slow thermochemical process that lasts from 30 to 90 minutes, in an inert atmosphere and temperature ranging between 200 ° C and 300 ° C. The electric power consumption for the grinding of torrefied wood raw material decreases with applied torrefact as a fuel (or additive combustible) in boilers. This process generates volatilization of hemicellulose and changes the properties of biomass, increasing the yield of roasted wood between 66% and 75% (Zwart, 2006; Sklar, 2009). Thus, the torrefied biomass pellet may increase its energy potential by about 1.3 times (Sklar, 2009). In addition to a higher energy density, close to that of mineral coal, between 20-23 GJ per ton, the roasting produces a pellet with low moisture content and low risk of biological degradation. For this reason, the production of roasted wood pellets becomes the object of research and important investments, in the hope of replacing coal in the production of electricity (Pirraglia et al., 2013). Regarding industrialization, torrefaction can be carried out before or after the biomass pelletization process (Ghiasi et al., 2014). When carried out before pressing the mixture, the resulting biomass presents greater water loss and drier, with the possibility of breaking and appearing a darker color. Torrified biomass facilitates pressing, reducing energy consumption by about 70% to 90% during this phase in the pelletization process (Shang et al., 2012; Liu et al.; 2013).

A certain progress is observed in this process, however, the available data on the industrial use of torrefaction technology is very limited. In relation to the economic context, the most effective method of utilization of wood raw material depends on the large-scale production to impact their market value. Even with new industrialization technologies, the production of wood pellets is the leading and most rapidly developing area of utilization of renewable biological sources of energy.

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