Environmental Engineering and Management Journal

August 2018, Vol.17, No. 8, 1791-1804
http://www.eemj.icpm.tuiasi.ro/; http://www.eemj.eu

"Gheorghe Asachi" Technical University of Iasi, Romania

EVALUATION OF ECO-EFFICIENCY BY MULTICRITERIA DECISION ANALYSIS. CASE STUDY OF ECO-INNOVATED AND ECO-DESIGNED PRODUCTS FROM RECYCLABLE WASTE

Elena-Diana Comăniță[1], Petronela Cozma[1], Isabela Maria Simion[1], Mihaela Roșca[1], Maria Gavrilescu[1,3]*

[1]"Gheorghe Asachi" Technical University of Iasi, "Cristofor Simionescu" Faculty of Chemical Engineering and Environmental Protection, Department of Environmental Engineering and Management, 73 Prof.Dr.Docent D. Mangeron Street, 700050 Iasi, Romania
[2]Academy of Romanian Scientists, 54 Splaiul Independentei, RO-050094 Bucharest, Romania

Abstract

Until now, humanity has strived to makes efforts for warranting the economic development on a sustainable way for well-being improvement, simultaneously with resource preservation and environmental protection. The industrial production processes, which generate added value and ensure people welfare are in connection with the environment regarding resource consumption and waste generation.

In order to work on a sustainable basis, industry should attain a balance between economy, ecology and community, in the long run. One way in which industry may depend not as much of natural resources and could reduce the environmental impacts is to improve its efficiency in using materials by recycling waste in a closed loop, in line with the principles of the circular economy.

It is largely recognized that economic efficiency - simultaneously with reducing environmental impacts are promising when they are guaranteed in the early phases of any process/product synthesis and design. Therefore, eco-innovation and eco-design are tightly connected with process/product/service eco-efficiency. Eco-innovation (ecological thinking or re-thinking) is related to all forms of innovations (technologies, products, services), which are able to bring new and robust business opportunities and benefits for the environment in terms of resources and impacts. Eco-design (sometimes denoted as environmental redesign) is a fully integrated design activity in which the environmental impact is checked against targets for improvement. The results of eco-innovation and eco-design application to close the cycles using production waste as resource need to be evaluated in terms of economic and environmental performance comparative with the conventional pathway.

Given these features, we applied the Multicriteria Decision Analysis (MCDA) to evaluate the eco-efficiency of a re-though and re-designed product based on eco-innovation and eco-design approaches, using waste production resulted from corrugated board and cardboard box manufacturing as raw material, and comparing it with the original, which is made from corrugated board sheets.

Key words: closed loop, corrugated board, Multicriteria Decision Analysis, production waste, resource

Received: January, 2018; Revised final: August, 2018; Accepted: August, 2018; Published in final edited form: August, 2018

1. Introduction

Most industrial systems are responsible for generating waste, sometimes in large quantities, and that puts pressure on the planet and limits its biocapacity to metabolize them and regenerate the natural resources (Gavrilescu and Ghinea, 2018; Velte et al., 2018). In order to minimize this pressure, the industry should shift from the current linear (*cradle-to-grave*) processes to cyclical (*cradle-to-cradle,*

* Author to whom all correspondence should be addressed: mgav@tuiasi.ro

cradle-to-gate) pathways (Bartolacci et al., 2017; Gavrilescu et al., 2018). Any industrial process, in its wholeness, may become a closed cycle in which the manufacturer considers the complete flow of materials and energy, from the input of raw materials and products manufacturing, throughout the life of the product, including eventual reuse or disposal. Manufacturers are responsible for their products until final disposal. The flow of materials can be considered either for an individual plant, a production factory, a group of factories involved in manufacturing of a certain product, an industrial sector, or the entire industry as a whole (Frosch, 1997). The main challenge involves overcoming the perception "waste - a problem” and rallying to the idea of "waste - a resource". The analysis of some waste management opportunities shows that most of the waste could be considered technologically potential resources and any material could be recovered (COM 571, 2011; EPRS, 2017; Gavrilescu and Ghinea, 2018; Ghinea et al., 2011).

Recycling and reuse are essentially options for connection between inputs and outputs of the process, by replacing the materials in the production development (Fig. 1). This method could provide circularity for the economy by minimizing the consumption of non-renewable resources, cost optimization, job creation and the development of business opportunities (Gavrilescu et al., 2018; Petraru, 2012).

At international level, integrated waste management issues are analyzed and approached from different perspectives. From economic and environmental point of view, waste management still requires a series of investigations in order to take the best decisions on the transformation of production waste with potential recovery into ecological materials and energy resources (Fava et al., 2015; Ghinea et al., 2012; McIntyre et al., 2013; Meleo, 2014).

Even if the strategic objectives of Horizon 2030 proposed that the level of recycling should be at least 50% of waste paper, plastic and glass by the year 2020, there are European countries currently registering lower rate of waste recovery comparing to European average (Eurostat, 2016) (Fig. 2). Currently, Romania faces with a problematic situation in the field of waste management, even if at the end of 2015 the European Commission adopted measures in the frame of circular economy to generate sustainable growth and consequently to create new jobs (Comăniță, 2016). Romania should ensure a recycling rate of 75% by 2025 and 85% by 2030 for paper and cardboard (EPRS, 2016). During the final use and disposal phase, the design process must also consider the means of recovering products and waste.

The development of closed loop systems requires a focus on the design stage of products and processes to minimize the consumption of materials and energy for the production and distribution of products, as well as their environmental impacts. Eco-innovation and eco-design contribute to a sustainable manufacturing since new ideas are integrated into the industrial process by redesign so as to generate added value with less environmental impact being therefore eco-efficient (Ghisellini et al., 2015).

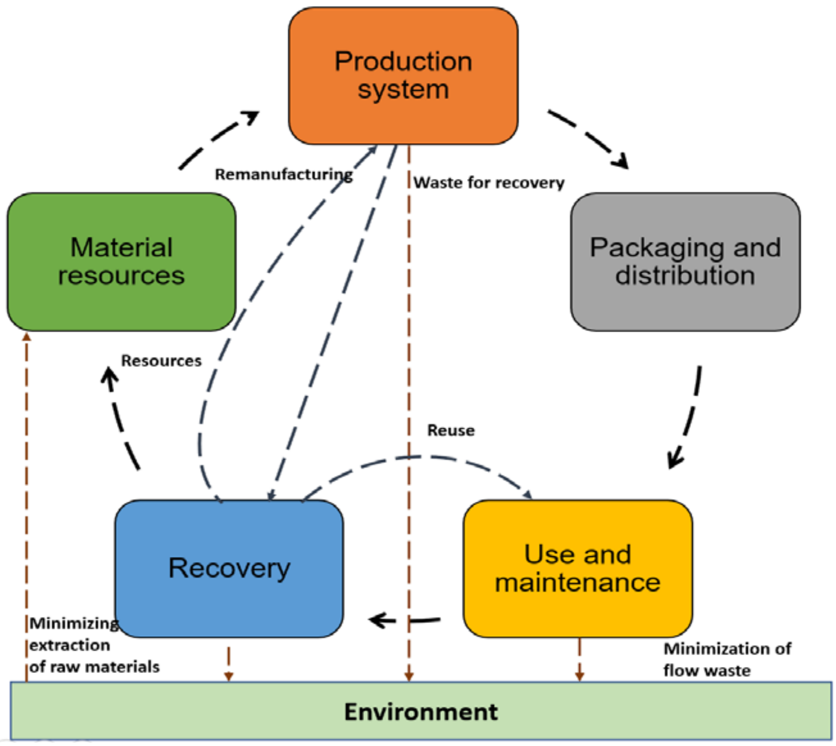

Fig. 1. Closed loop production systems (adapted upon OECD, 2009)

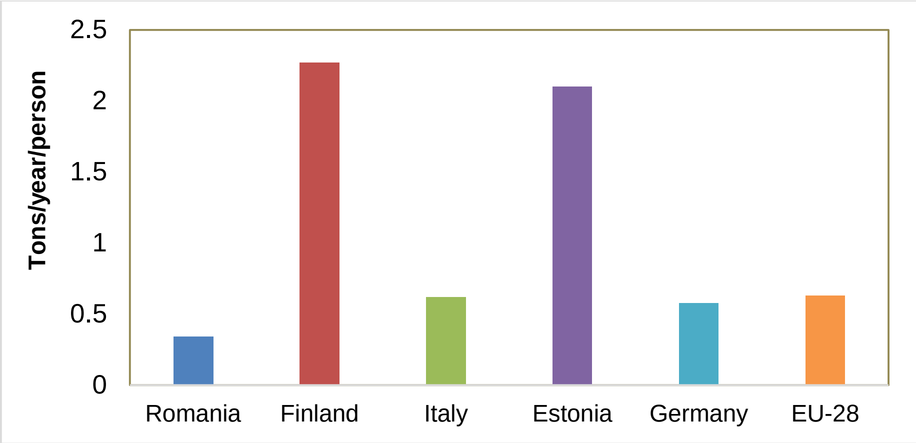

Fig. 2. Recycling rate of production waste in Europe in 2016 (adapted upon Eurostat, 2016)

Applying eco-design strategies is very useful in an industrial production system because it focuses on eliminating the environmental impact from the first stage of design and production (OECD, 2009). As it is in the upstream area of the decisions, eco-design is a preventive approach (OECD, 2010). Eco-design contributes to the prevention of waste generation from industrial systems and to minimization of environmental impacts by reducing energy consumption, water and air pollution (Gavrilescu, 2011; McIntyre et al., 2013). Eco-innovation is a component of innovation that discovers new paths towards sustainable economic activity (Gavrilescu et al., 2018; Slimane et al., 2015).

In order to achieve the strategic objectives of a sustainable system in the field of waste management, it is necessary to measure and quantify the technical, economic and environmental performance of the process and product in terms of eco-efficiency. The assessment can be done by applying specific tools such as: Life Cycle Assessment (LCA); Cost-Benefit Analysis (CBA); Multi-Criteria Decision Analysis (MCDA) (Gavrilescu, 2011; Simion, 2013).

In this context, the present study developed an analysis of the eco-efficiency, expressed in environmental, technical and economic terms for a redesigned product using waste production resulted from a corrugated board and cardboard box manufacturing as raw material, compared to the original, which is made from corrugated board sheets.

To achieve this goal, we went through MCDA specific steps, establishing process boundaries, assessing of technic, economic and environmental criteria, and finalizing with sensitivity analysis.

2. Waste from industrial production processes

2.1. Environmental impact of production waste

The rapid progress of the industry has led to the generation of huge quantities of solid and liquid production waste. The majority of these wastes come from industrial sectors such as sugar, pulp and paper, fruit and food processing, meat processing, beverage processing and others (Comăniță et al., 2015; Mymrin et al., 2018; Su et al., 2018). Despite the fact that a series of sustainable waste management alternatives were adopted, such as pollution prevention and control measures, production waste is still generally improperly disposed, discharged into various fields, or discharged into the water without proper treatment, thus becoming an important source of environmental pollution and health hazards (Petraru and Gavrilescu, 2010; Simion et al., 2017).

Depending on the industry, production waste can be classified in two major categories (EPA, 2005; Guerrero et al., 2013; Soler et al., 2017): *(i) hazardous production waste* (can cause a health or environmental hazard even if they are generated on their own or in contact with other wastes), *(ii) non-hazardous production waste* (is not toxic, does not present a hazard and do not require special treatment). So, globally, one of the major environmental problems facing the industry is directly related to waste generation and emissions (Mantovani et al., 2017). Typically, waste management strategies are based on end of pipe technologies, for example, solid production waste are stored in uncontrolled warehouses (without previous recycling) (Hammar and Löfgren, 2010). Moreover, the economic and environmental costs of production waste treatment technologies are high, and there are serious obstacles acquiring technologies to recover these wastes (Ghinea, 2012).

Research on the reuse of production waste is of interest, since it can reduce the environmental impact of the new material or product and also brings some economic benefits (Mantovani et al., 2017). Fig. 3 illustrates a statistic according to Eurostat (2018) regarding the main branches of industry generating production waste, as well as the percentage of waste generated by each industry: plastic processing and production, paper and cardboard processing, glass processing and production, food industry, construction industry, ore processing, energy industry, and others. As it can be seen in Fig. 3, pulp and paper industry generates a relatively large amount of waste (17% from the total production waste).

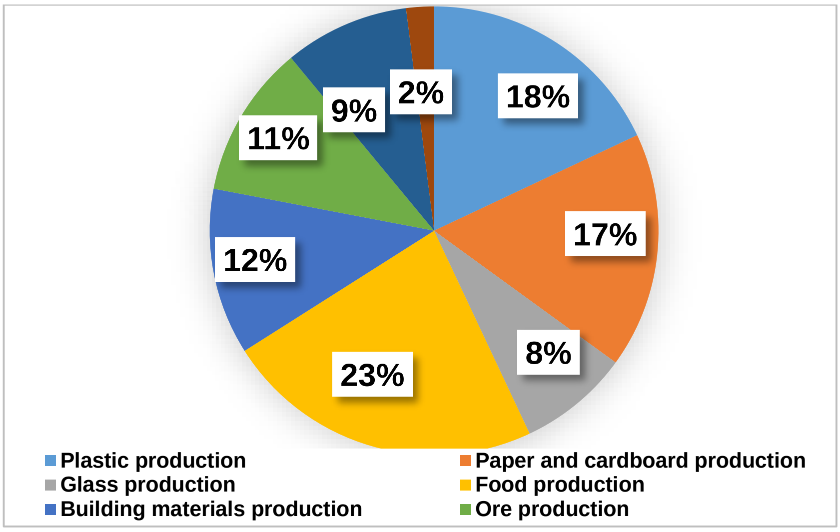

Fig. 3. Percentages of waste generated by each branch of the industry, at global level, according to Eurostat (2018)

The cardboard production is a continuous process where multiple layers of paper are glued together over other corrugated or straight stripes. These stripes are cut automatically resulting in waste in small or large sizes, which are abandoned in the production line and should be removed as soon as possible. Paper and cardboard materials are used for a large variety of products, in particular for packaging. All of these materials, at the end of their life become waste (Gavrilescu et al., 2018). Almost 20% of production waste from paper and cardboard and other materials are recyclable products. Therefore, a first step to improve the management of production waste is to recover recyclable waste. Comparative to European level, where more than 70% of paper and cardboard waste is recycled, at national level only approximate 25% is achieved (da Cruz et al., 2014; GSS, 2018). Recycling a tone of cardboard waste involves saving a number of 15 trees from cutting and also saving 4,100 kWh of electricity and 31,780 liters of water. In the same time, one tone of recycled cardboard waste can save a surface of 4 cubic meters that could be an unbuilt waste landfill (Rahman et al., 2016).

2.2. Strategies for sustainable use of industrial production waste

At present, synthesizing, designing and exploiting production systems means more than choosing and combining production elements with the aim of generating high productivity and economic efficiency. Thus, it has become a necessity to consider all types of resources involved as inputs into a production system, as well as valuable products for distribution to consumers along with the waste resulting from production processes in order to take the most appropriate actions such as reduction, reuse or recycling (Ghinea et al., 2016; Gavrilescu et al., 2018).

According to Eurostat statistics at the level of 2015, Romania generated 281 tonnes/year/capita production waste with recovery potential (packaging waste, plastic bottle, metallurgical sectors), compared to the European Union (EU) average of 459 tonnes/year/capita (Comăniță et al., 2017; Eurostat, 2018). Because of the aggressive use of non-renewable resources, there is more and more emphasis on the abandonment of linear economic models (the "cradle to grave" approach) to adoption of new models for sustainable resource management and energy, by replacing raw materials with recoverable materials (COM 398, 2014; Velte et al., 2018).

Obviously, the performance of different industrial systems occurs when they are capable of exploiting and managing waste, especially those resulted during production step, which are usually perceived as loss of production (Velte et al., 2018). Applying various alternatives such as: source reduction, in-plant recycling, on-site or off-site recycling, recovering valuable components from waste, a transition from a linear economy (Fig. 4) to a circular one (Fig. 5) can be achieved by closing the production loop. In this way, the end-of-life products, as well as production wastes are collected, conditioned and reused or recycled to increase material efficiency, cost efficiency and environmental performance of industrial companies (Gavrilescu and Ghinea, 2010; Velte et al., 2018). All of these aspects are closely related to improvements in environmental efficiency that would require a reduction in resource consumption, reducing environmental impact throughout the life cycle of processes and products, and extended producer responsibility (COM 398, 2014). The Horizon 2020 program has set out the strategy for smart, sustainable and inclusive growth - the Europe 2020 strategy - according to which progress towards a circular economy is now considered the focus of resource efficiency concerns.

Fig. 4. The linear economy model in industrial systems (taken from Bosmans, 2014)

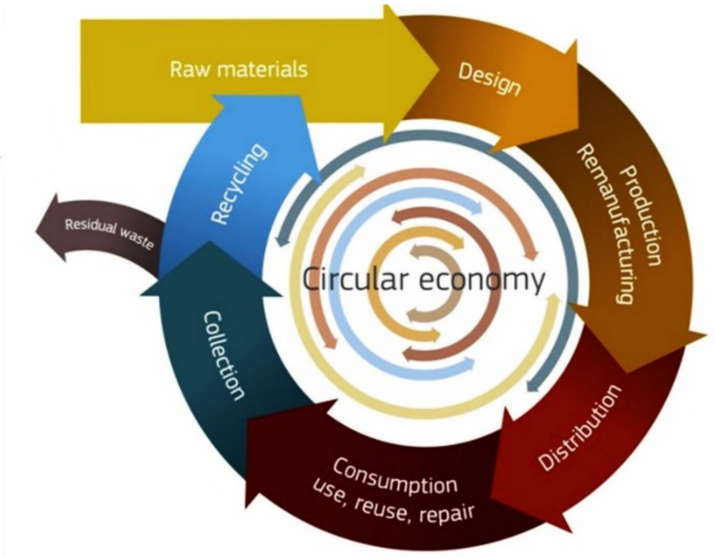

Fig. 5. The circular economy model in industrial systems (taken from COM 398, 2014)

Waste prevention, re-use and other related measures to eco-innovation and eco-design could save € 600 billion or 8% annual turnover for EU-28 companies together with a total reduction in greenhouse gas emissions of 2% - 4%.

Circular economy involves the use of a product for a long time, even when it is at the end of its life cycle, so it will continue to be productively used and to generate benefits (Fig. 5). One of the ways to close the production cycle is to use the waste generated during the production process as a result of incomplete raw material processing (Gavrilescu et al., 2018; Ghisellini et al., 2015). Keeping the value of products and materials as long as possible, and generating small amounts of waste, the world economy would become more competitive and resilient, and also the pressures on biological capacity of planet may be reduced.

Based on knowledge transfer, eco-innovation and eco-design practices, the manufacturing processes must re-use production waste as ecologic products "at the factory", by moving from the classic approach "from cradle-to-grave" to more sustainable approaches as "cradle-to-gate" or "cradle-to-cradle", extending thus the life cycle of materials and waste as valuable products (OECD, 2010). In this way, a substantial reduction in the amount of cardboard waste can be achieved by recycling and closing the production loop at the factory and outside the plant (avoiding the use of virgin materials such as trees), which will increase the capacity of the natural system to retain carbon dioxide and will avoid emissions to the atmosphere during processing of virgin fibers (Wass et al., 2010). Eco-efficiency is one of the best tools to promote transformation from unsustainable development to sustainable development. According to OECD (1998), "eco-efficiency expresses the efficiency with which ecological resources are used to meet human needs. It can be considered as a ratio of an output divided by an input: the "output" being the value of products and services produced by a firm, a sector or the economy as a whole, and the "input" being the sum of environmental pressures generated by the firm, sector or economy". Eco-efficiency aims to create a harmony between ecology and the economy, where production activities do not lead to increased negative effects on the environment**.** The main benefits of eco-efficiency are: reduction of energy, water and raw materials use, reduction of waste and pollution levels, increased service intensity. The application of eco-efficiency indicators in the technic-economic and environmental sectors is usually based on the ratio of product or service value to environmental impact (Wass et al., 2010).

World Business Council for Sustainable Development (WBCSD) discussed the eco-efficiency goals as follow: "eco-efficiency is reached by the delivery of competitively-priced gods and services that satisfy human needs and bring quality life, while progressively reducing ecological impacts and resource intensity throughout the life cycle, to a level at least in line with the earth's estimated carrying capacity" (Ehrenfeld, 2005; OECD, 1998).

Considering this framework able to enhance eco-efficiency in the cardboard packaging production, we applied principles and practices of eco-innovation and eco-design in our study. As a result, an eco-product with ”cradle-to-gate” life cycle and zero waste was created. To achieve our goal, we developed an eco-efficiency evaluation in the context of Multicriteria Decision Analysis for a redesigned product using production waste resulted in a corrugated board and cardboard box manufacturing as raw material, compared to the original product, which is made from corrugated board sheets, by applying eco-innovation and eco-design principles and practices within a Romanian manufacturer specialized in cardboard packaging production.

3. Multicriteria Decision Analysis of production waste

3.1. Multicriteria Decision Analysis methodology

Multi-Criteria Decision Analysis (MCDA) is a methodology that aims to support decisions making processes (Generowicz et al., 2011). MCDA methods have been developed to improve the quality of decisions, involving several criteria, making the choices more explicit, rational and efficient (Gavrilescu and Ghinea, 2010; Generowicz et al., 2011).

The purpose of MCDA methods is to create a structured process to identify the objectives, to create alternatives and to offer the possibility to compare them from different perspectives (BALKWASTE, 2011). Multicriteria Decision Making methods can be successfully applied to obtain realistic solutions to complex issues such as waste management (Generowicz et al., 2011; Ghinea et al., 2014; Soltani et al., 2015); water management (Hyde et al., 2005; Pedrero et al., 2011; Scholten et al., 2015; Sudhakaran et al., 2013) and energy resource management (Kowalski et al., 2009; Troldborg et al., 2009). The multi-criteria decision analysis involves the following steps (Comăniță, 2016; Ghinea, 2012; Petraru, 2012; Simion, 2013):

- establishing the decisional context;
- establishing the objectives of the evaluated project and its feasibility;
- defining options/alternatives to be considered;
- identifying and defining all relevant criteria for the project under consideration;
- creating a matrix that describes the performance of each option according to established criteria;
- standardizing the scores set for each criterion (usually with values ranging from 0-1 to 100);
- calculating the weight of each criterion in the decision-making process;
- options hierarchy - choosing the optimal option;
- examining the results;
- sensitivity analysis for the validation of the alternative chosen.

Multi-Criteria Analysis methodology includes several methods such as (Choi et al., 2015): Analytical Hierarchy Process (AHP); Elimination et Choix Translator in Realité (ELECTRE I; ELECTRE II; ELECTRE III); Organization, Range and Syntheses by Donnes Relationnelles (ORESTE); Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE); Simple Multi-Attribute Ranking Technique (SMART).

One of the most applied methods in evaluating multi-criteria decisions is the ELECTRE method developed by Choi et al. (2015). It has been developed in France and is predominantly applied in European countries. This method offers the possibility of working with discrete criteria, both quantitative and qualitative, and also gives a complete ordering of alternatives (Choi et al., 2015). Another method is AHP developed by Thomas L. Saaty, which is based on the principle of dividing a complex problem into a hierarchy, for which the goal (decision point) is at the top of the hierarchy, followed by the criteria and subscriptions that are represented schematically of the levels and sub-layers of the hierarchy (Chen et al., 2017; Saaty, 2008; San Cristobal, 2012).

3.2. Application of MCDA methodology for the assessment of eco-efficiency in the cardboard packaging manufacturing sector

In order to evaluate the economic, technical and environmental performances of production waste, two methods included in MCDA methodology were applied in this paper: ELECTRE and AHP. Here, Multicriteria Decision Analysis was proposed as a complete and complex methodological framework for conducting a sustainability-oriented design. The analysis will involve some basic steps, irrespective of the method applied: (i) identification of objectives; (ii) documentation on the possible options for achieving the objectives; (iii) identification of the criteria used to compare the options; (iv) option analysis; (v) option ranking and selection; (vi) sensitivity analysis and validation of alternatives resulted from decision process; (vii) decision making and application; (viii) feedback from manufacturer.

The study will provide basic information useful in recommending the application of eco-innovation and eco-design principles and practices to a Romanian manufacturer specialized in cardboard packaging production, for the re-evaluation of waste production according to the circular economy concept, so as to increase production and product eco-efficiencies. Moreover, the research group will be able to perform an experienced knowledge transfer based on well-documented scientific support, able to ensure a balance in economic, social and environmental trade-offs for the manufacturer by taking into account multiple goals related to the allocation of resources and investments, eco-efficiency, to avoid contradictory opinions among diverse stakeholders.

3.3. Description of the analyzed production contour and product manufacturing

Corrugated cardboard packaging has a carbon footprint of 0.459% in Europe. Replacing cartons with other alternative materials would increase the carbon footprint for this industry. Considering the carbon balance, it can be said that using corrugated cardboard packaging, extending the life cycle and preventing product degradation brings major benefits. The most important benefits for the environment generated by eco-product considering corrugated board and cardboard box manufacturing waste as raw material are the reduction of some production waste which can be reintegrated in the production of paper for packaging.

Under these circumstances it has been identified the necessity for the Romanian manufacturer to look for value in all the production waste through reuse by using strategies and technological solutions based on the eco-innovation and eco-design principles, so that the production cycle can be efficiently closed in order to obtain an eco-friendly product, with high potential on the market and a large constructive flexibility, as specified by the demands of the beneficiaries. Based on the deficiencies identified and summarized in technological process, a set of preliminary improvement alternatives were developed to address safety, geometric and operational deficiencies identified along the corrugated board manufacturing process.

In this context, two scenarios were developed and evaluated in terms of economic, technic and environmental analysis: cardboard packaging manufacturing using cardboard sheet (Process 1) and redesigned product using production waste resulted in corrugated board and cardboard box manufacturing as raw material (Process 2).

For process assessing a short description and the limits of the system of the technological scheme for corrugated board and packaging manufacturing is presented in Figs. 6-7. In the **first step**, after conditioning, the paper is corrugated and then non-corrugated layers are glued over the corrugated paper to form a continuous sheet of cardboard. The cardboard is dried and then cut into the required dimensions of the cardboard plate for packaging manufacturing. In **step 2**, the cardboard is cut to the size required to manufacture the packaging. Packaging boxes are made by cutting the cardboard, then overlapping and gluing the edges.

In this study, 10t of corrugated cardboard was chosen as functional unit. All stages for both ELECTRE and AHP methodologies have been completed.

3.3.1. Application of ELECTRE method

The ELECTRE method serves to compare variants $V_1, V_2, ..., V_m$ in terms of criteria $x_1, x_2, ... x_n$. ELECTRE method is based on two groups of indicators, namely: concordance indicators (Cc) and disagreement indicators (Cd). By comparing two variants, V_j and V_i, the concordance indicators highlight the favorable aspects of V_j versus V_i, while the disagreement indicators highlight the unfavorable aspects of V_j versus V_i (Buchanan and Sheppard, 2012). The principle of this method is based on the idea that each alternative is in competition with the others and the choice of an alternative considered to be the best, should be done only if it is really better than all the others. In other words, the optimal variant is the one that surpasses the other variants (Buchanan and Sheppard, 2012).

In order to identify the optimal action plan, we proposed two variants: cardboard packaging manufacturing using a cardboard sheet (Process 1) and a redesigned product using production waste resulting in corrugated board and cardboard box manufacturing as raw material (Process 2), marked **V1** and **V2** respectively.

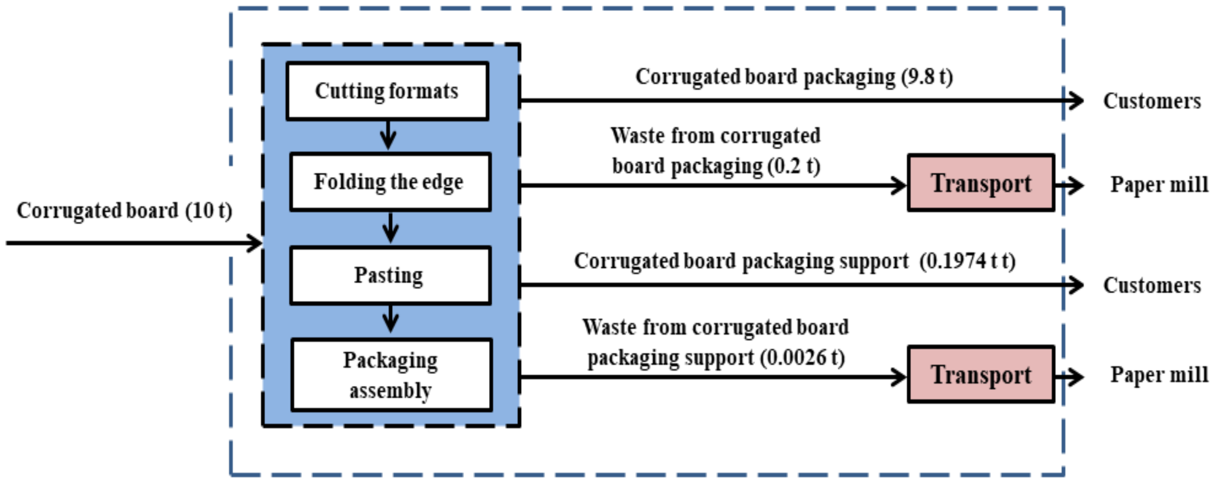

Fig. 6. Boundaries for Process 1

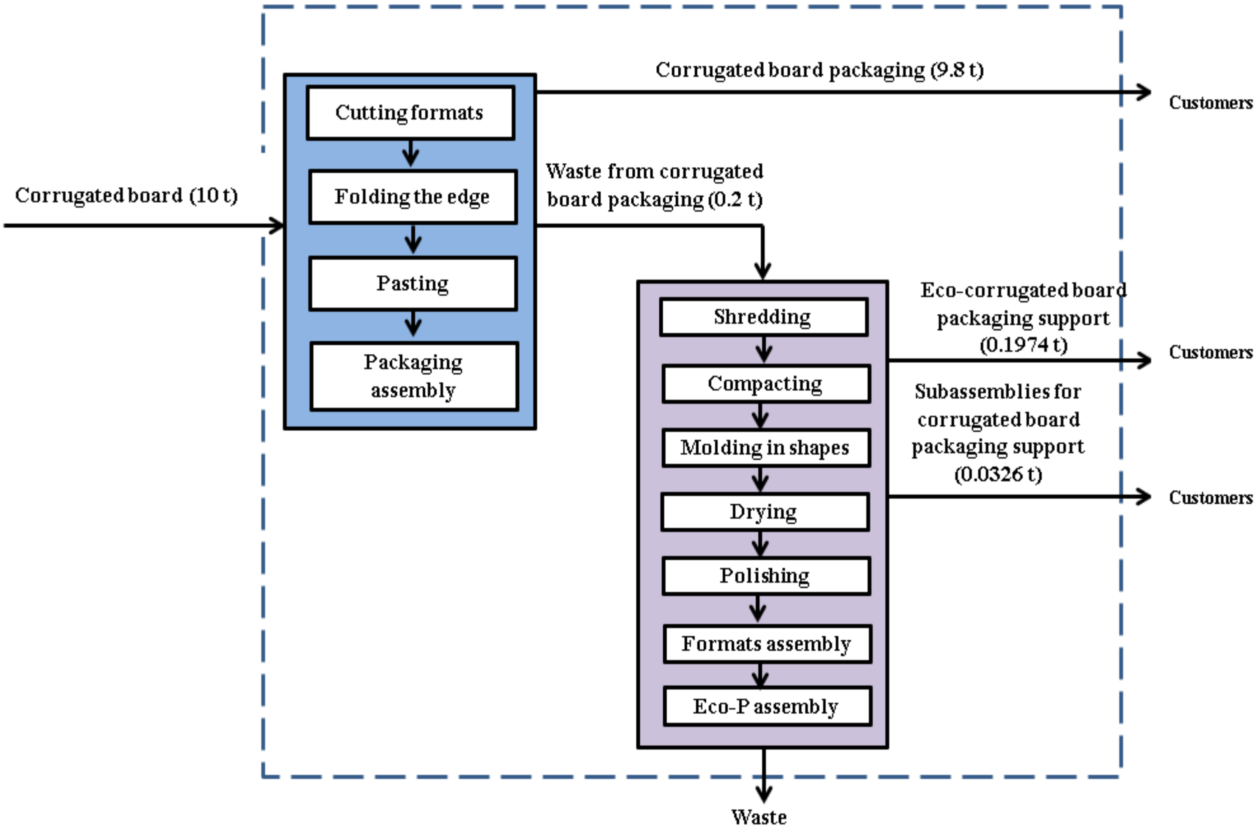

Fig. 7. Boundaries for Process 2

The following criteria, labeled C1 - C6, were the basis for establishing these variants:

C1 - Benefit achieved by applying the solution (EUR);
C2 - Cost application process (EUR);
C3 - Waste reintegration in the production process (mark);
C4 - Harmonization with EU priorities for 2020 - Zero Waste (mark);
C5 - Recovery of production waste (%);
C6 - Obtaining ecological products (%).

Each variant **V1 – V2** has been assessed according to the criteria **C1 - C6** set and with the help of the ratings it was constructed the matrix called matrix of consequences (Figueira et al., 2013). Once the scoring standards are set, the grades in the Matrix of Consequences with the grades corresponding to each criterion are replaced, resulting in the score matrix (Figueira et al., 2013). In order to evaluate the variants for criteria 3 and 4 the following qualifiers are awarded: S-sufficient, B-good, FB-very good; ND-non-degradable, UD-readily degradable, FUD-very easily degradable. The following steps were surveyed: determining the coefficients of importance K_j for each criteria, determining the matrix of utilities a_{ij}*, calculating the concordance indicators, calculating the discordance indicators. The equations used in these steps are shown in Table 1.

3.3.2. Application of AHP method

AHP methodology supports decision making and decision-makers based on a set of criteria that integrate technical, economic, environmental and social issues. This method is based on the principle of dividing a complex problem into a hierarchical scheme in which the object (decision point) is at the top of the hierarchy, followed by the criteria and sub-criteria, which are schematically represented by the intermediate levels and sublevels of the hierarchy (Fig. 8).

The basis of the hierarchy consists of the decisional alternatives that can be independently analyzed from each other. AHP compares the criteria or alternatives to a pairwise criterion that allows for the structuring, measurement and / or synthesis of evaluated systems. Building the decision hierarchy allows the decision maker to evaluate its elements (according to relative preference) by comparing them by pairs (Forman and Gass, 2001). AHP uses a relative scale (reports) and does not involve units of measurement in comparing the results (Ishizaka and Labib, 2009). Saaty (2008) proposed a scale of 1-9 to allow the estimation of the intensity of the preferences between two elements of a problem and the weighting of quantifiable and non-quantifiable elements.

Performance evaluation of the cardboard packaging manufacturing from cardboard sheet (Process 1) and a redesigned product from production waste (Process 2), has been carried out in relation to the specific criteria mentioned in Fig. 9 of a different nature which are often in conflict.

Table 1. Equations used to apply the ELECTRE method

No	*Stage*	*Equations applied*
1	Determining the coefficients of importance K_j for each criteria	$$K_{ij} = \frac{\sum n_{ij}}{\sum\sum n_{ij}}$$ where: Σn_{ij} is obtained for the criteria that correspond to the variants, $n_{ij} \geq n_{ij}$; K_{ij} - the coefficients of importance given to the criteria. The coefficients of importance have values ranging from 0 to 1 and show how variance V_i exceeds a variant V_j.
2	Determining the matrix of utilities a_{ij} *	$$U_{ij} = \frac{a_{ij} - (a_{ij})_{u=0}}{(a_j)_{u=1} - (a_j)_{u=0}}$$ where: U_{ij} is the coefficient of importance of criterion j; a_{ij} the utility of variant V_i for criterion j.
3	Calculating the concordance indicators	$$C_{ViVj} = \frac{1}{\sum_{k=1}^{n} Kj} \sum Kj; a_{gj} \geq a_{hj}$$ where: C_{ViVj} is the concordance indicator; Kj - the coefficient of importance of criterion j; a_{gj}, a_{hj} - appreciation notes, depending on, utility.
4	Calculating the discordance indicators	$$D_{ViVj} = \begin{cases} a_{gj} > a_{hj} \\ \frac{1}{d}\max\left|a_{gj} - a_{hj}\right|; a_{gj} \leq a_{hj} \end{cases}$$ where: d represents maximum distance, between the a_{ij} scores of appreciation given for the disagreement indicator; d = 1.

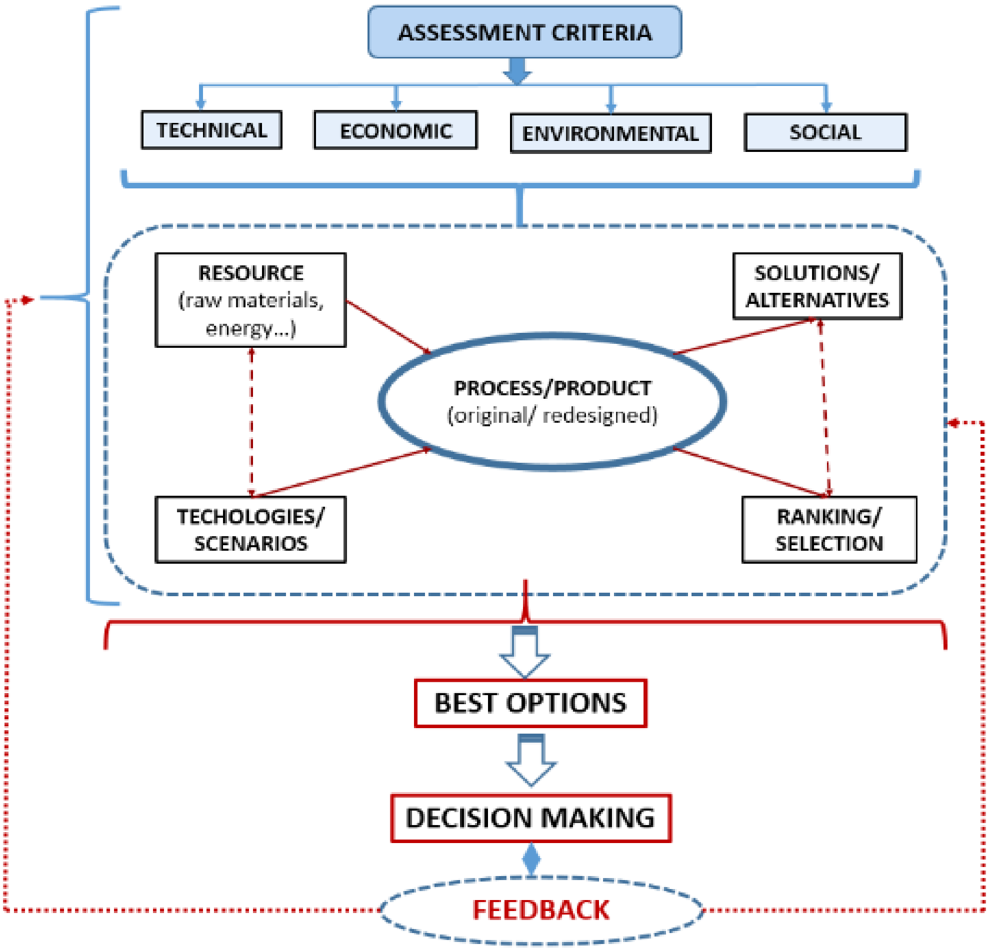

Fig. 8. Steps in application of AHP method (adapted upon Comăniță, 2016)

Table 2. Equations used to apply the AHP method

No	*Stage*	*Equations applied*
1	Calculation of relative weights	$Wr_{Rx_{i=1}^n} = \frac{\sum RxC_{i=1}^n}{\sum RxTC_{i=1}^n} \cdot 100$ where: $Wr_{Rx_{i=1}^n}$ is the relative weight of the score given to the criterion and according to the scale of the Ranking method, and $\sum RxC_{i=1}^n$ is the sum of the scores awarded by each expert to the criterion *i*. $\sum RxC_{i=1}^n$ is the sum of the scores assigned to each criterion in part.
2	Calculation of combined weight	$WC_{i=1}^n = \frac{Wrx_{i=1}^n - Wrz_{i=1}^n}{2}$ where: $WC_{i=1}^n$ represents, the combined weight of the criteria "*i*", $Wrx_{i=1}^n$ is the relative weight of the score given to criterion *i*, in relation to the Ranking scale and $Wrz_{i=1}^n$ represents the relative weight of the score assigned to criterion *i*, in relation to the scale of the Rating method.

Ranking and Rating methods have been applied to identify and select relevant criteria and indicators for process evaluation. Decision criteria are evaluated through particular scores on the Ranking and Rating methods (Forman and Gass, 2001). In the case of the Ranking method, scores are included between values 1 and 9, and for the Rating method, scores ranged from 1-100 (Forman and Gass, 2001). The team of experts involved in this study consists of: environmental expert, design engineer, government representative, consumer. Each expert was asked to complete the list of decision elements (performance indicators assigned to the criteria) in order of ranking and then to give to each decision element a score between 0 and 100 (rating). After these steps, the analysis of the experts' response was carried out. Through the set of values corresponding to the proposed methods, the Ranking and Rating amounts were calculated, and are further used to calculate the relative weight of each given value. The equations used in these steps are shown in Table 2.

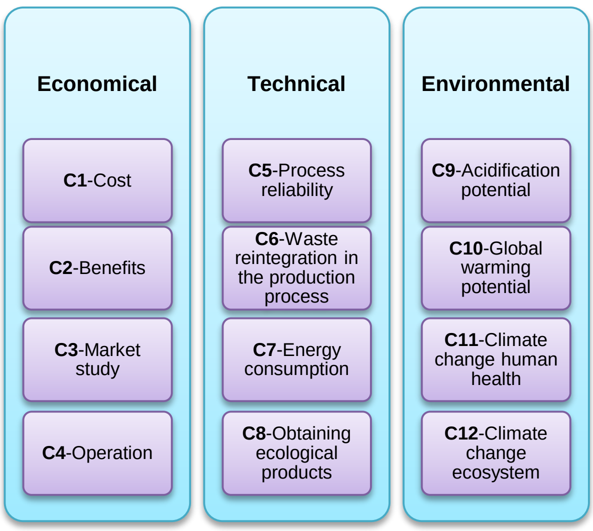

Fig. 9. Criteria considered for the evaluation

3.3.3. Application of eco-efficiency method

The application of eco-efficiency indicators in the technic-economic and environmental sectors is usually based on the ratio of product or service value to environmental impact (Eqs. 1-2).

$$Eco\text{-}efficiency = \frac{\text{Enhancing the quality value of product}}{\text{Environmental impact of product reducing the impact}} \quad (1)$$

$$Eco\text{-}efficiency = \frac{\text{Economic Output}}{\text{Environmental Cost}} \quad (2)$$

Environmental costs can be associated with:

• Pollution emissions (CO_2 or SO_x emissions, biochemical oxygen demand, etc.);
• Resource-used (energy or water used);
• Costs associated with an environmental burden (traffic congestion costs).

Economic output can be:

• Value added of benefit (GDP per capita);
• Unit of product or service (per km, per m^2);
• Costs associated with an environmental burden (traffic congestion costs)

4. Results and discussion

The results obtained using the ELECTRE method indicated that Process 2 is the alternative that surpasses Process 1 from economic, technic and environmental point of view. This result reveals that, Process 2 is viable and its implementation will bring environmental, economic and technic benefits (Fig. 10). In addition to environmental benefits, this eco-innovate product can also bring economic and social benefits that consist of: realizing the different constructive and functional variants of Eco-P, depending on the destination and the requirements of the beneficiaries, using the existing experience and equipment, without significant investments.

AHP method application involved the use of Rating and Raking methods and the pairing method. According to the final score obtained it can be seen that Process 2 is more efficient than Process 1, from the environmental, technical and economic point of view. The final score obtained for each scenario after we applying pairing method was: Process 1 - 1.48, Process 2 -2.43. After analyzing the results of pairing method, it was found that the values obtained for Process 1 indicates a low performance in terms of selected criteria (Fig. 11). Also, the results highlighted that Process 2 is the most suitable alternative in terms of environmental, economic and technical aspects because eco-products are 100% recyclable, biodegradable, comply with legal regulations, and therefore will bring benefit to the environment because the life of an Eco-P is extended and after reuse, the product can return to the paper recycling chain.

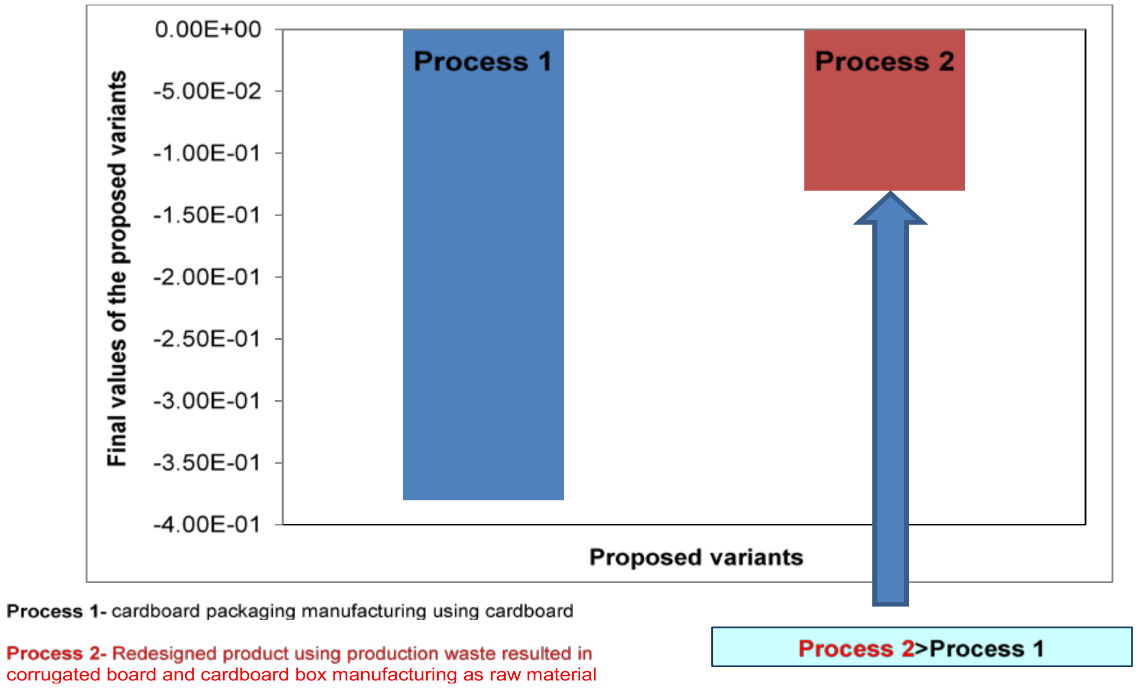

Fig. 10. Comparative analysis of corrugated packaging alternatives from technical, economic and environmental point of view - ELECTRE method

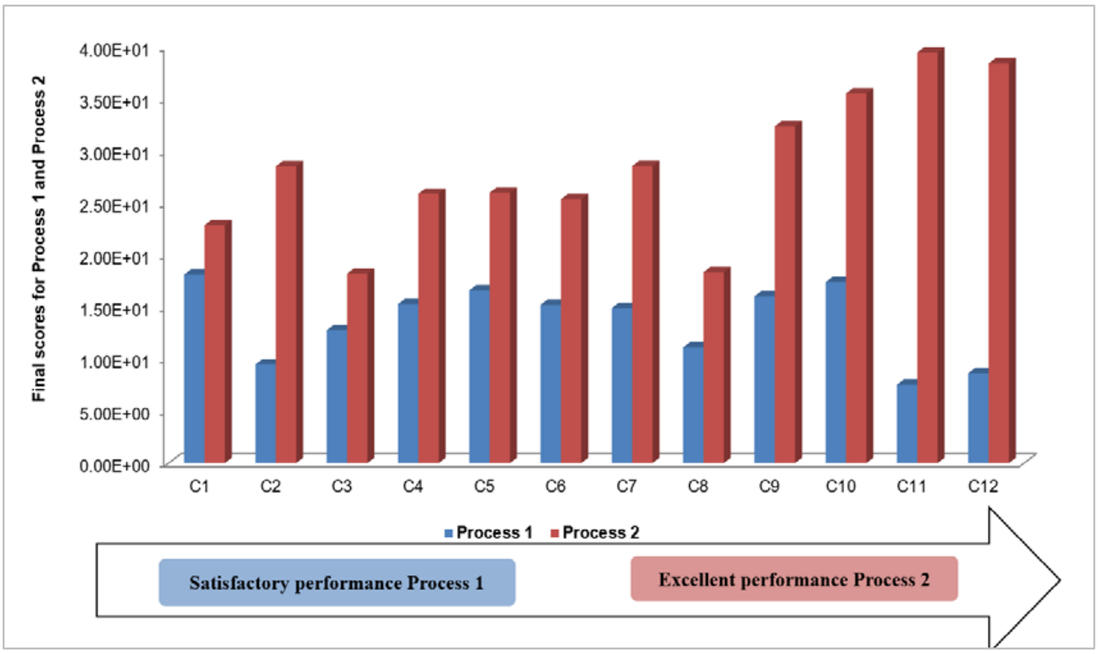

Fig. 11. Comparative assessment of technical-economic and environmental performances of the corrugated packaging alternatives- AHP method

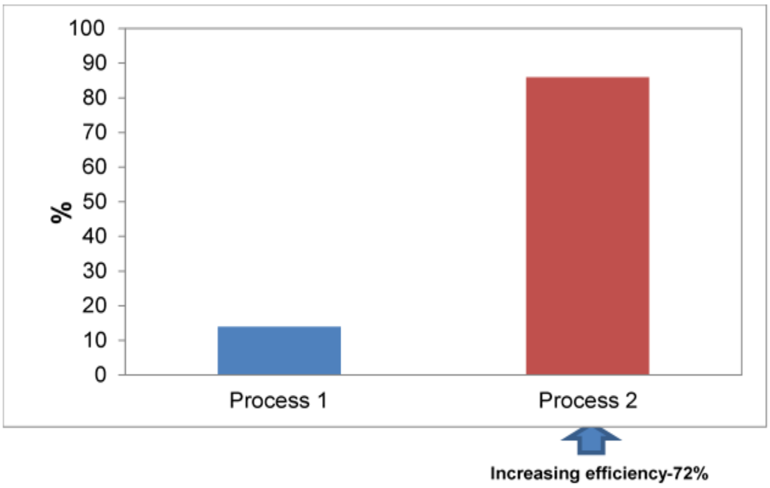

Fig. 12. Analyzing the eco-efficiency progress of the corrugated packaging alternatives

The assessment of technical, economic and environmental performances based on ELECTRE and AHP methods and eco-efficiency ratio revealed that Process 2 has a high eco-efficiency, which means that we can reuse the production waste so as to close the loop and extend the life cycle of cardboard in an eco-efficient way (Fig. 12).

The analysis identifies the potential of the Romanian manufacturer to close the production cycle by efficiently reusing of production waste, from the production process. In this way, the Romanian company can ensure a longer life cycle of production and products, and sustainable strategies in activities and decisions regarding production process and development leading towards zero emissions target in line with the principles of circular economy.

5. Conclusions

According to the amount of production waste that are largely dependent on the technological progress, the industrial production needs to be eco-efficient by combining the economic efficiency with low environmental impacts and social benefits.

The objective of present study was to analyze the corrugated cardboard production potential to apply the circular economy principles by closing the loop, based on a case study represented by a Romanian manufacturer, considering sustainable production principles based on eco-innovation and eco-design.

The modern technology available at Romanian manufacturer, which is the subject of our study, consists in two main stages: 1 - corrugated cardboard production and 2 - corrugated cardboard packaging manufacturing. Therefore, the purpose of this study was to identify and assess the need of the economic agent to recovery of all production waste by re-use in the process, applying strategies and technology solutions based on eco-innovation and eco-design which closes the production cycle in an eco-efficient way, to achieve an ecological product with economic potential and wide versatile and functional flexibility in accordance with customer requirements.

In this context, the processes proposed (*Process 1*- cardboard packaging manufacturing using cardboard sheet, *Process 2*- redesigned product using production waste resulted in corrugated board and cardboard box manufacturing as raw material), were evaluated based on two methods considering three sustainable development indicators such as economic, environmental and technical, so as to establish the most efficient process.

The assessment of technical, economic and environmental performances after applying ELECTRE and AHP methods revealed that *Process 2*- redesigned product using production waste resulted in corrugated board and cardboard box manufacturing as raw material has a high eco-efficiency.

The eco-efficiency analysis on the potential in cardboard manufacturing sector, demonstrates that, based on the stated assumptions, the *Process 2* is more eco-efficient than *Process 1* when the product to be manufactured is redesigned and the waste resulted from *Process 1* are used for obtaining an eco-redesigned-product. In fact, production costs are higher for *Process 1* and production waste resulted must be decreased to offset them in the use phase and to obtain a positive net cost reduction.

When production waste resulted from *Process 1* are reduced and the Eco-product is optimal designed, *Process 2* become the most eco-efficient manufacturing technology in terms of economic, environmental and technologic results.

In order to achieve a high eco-efficiency on corrugated board and packaging manufacturing process, the wastes are reintegrated by reprocessing and life cycle extending.

Acknowledgements
This work was supported by two grants of the Romanian National Authority for Scientific Research, CNCS – UEFISCDI, project number PN-III-P2-2.1-BG-2016-0130, Contract 64BG/2016 and project number PN-III-P4-ID-PCE-2016-0683, Contract 65⁄2017.

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