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Original
Exergoeconomic analysis of a Mechanical Biological Treatment plant in an Integrated Solid Waste Management system including uncertainties / Russo, Sofia; Verda, Vittorio. - In: ENERGY. - ISSN 0360-5442. - 198:(2020), p. 117325. [10.1016/j.energy.2020.117325]

Publisher:
Elsevier

Published
DOI:10.1016/j.energy.2020.117325

Exergoeconomic analysis of a Mechanical Biological Treatment plant in an Integrated Solid Waste Management system including uncertainties

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Abstract

Municipal Solid Waste (MSW) disposal is still a crucial issue, which is influenced by heterogeneous factors (political, social, economic, technological). The Mechanical Biological Treatment (MBT) plant is an important element of an Integrated Solid Waste Management (ISWM) system. These plants are aimed at separating the light and dry fraction of the Unsorted Waste (UW) from the wet one, producing the Refused Derived Fuel (RDF), and recovering the metal parts. In the present work, an Exergoeconomic analysis is performed on two MBT plant structures in order to assess the unit exergy-based cost of products and allocate the irreversibility associated to each equipment. A linear variation of degree of Selective Collection (SC) of single materials (± 30% respect to the base case) shows that the major influence on production costs is associated to the SC of plastic. A Monte Carlo simulation is then carried out by sampling from distributions of external (waste composition) and internal (energy consumption) uncertain variables. The resulted mean values (μ) and standard deviations (RStD) can be useful at the time of designing a new plant. The influence of the internal variable is definitely lower than the external one, with values of RStD more than 90% lower.

1. Introduction and state of art

Over the last years, in the European countries, a growing attention has been paid to Municipal Solid Waste (MSW) treatment options, in order to find valuable alternatives to landfill and enhance the value of the wastes by recovering materials and energy. Development of an Integrated Solid Waste Management (ISWM) system is still a crucial issue, since it involves political choices other than technological and social factors. MSW generation and characteristics depend on several elements: location and density of population (geographical factors) [1], [2], habits and wealth of people (social and economic factors) [3], [4], period of year and touristic activity of the area (seasonal factors) [5], [6]. In this context, the recycling policies, the level of consciousness of the population and the type of collection (traditional or Kernel collection) have a strong influence on the degree of Selective Collection (SC) [3]. The collected material streams are directed to the recycling plants; the outlets of these systems are manufactured products, waste from the recycling process and rejected material, which cannot be treated for economic or technical reasons (i.e. lack of request in the market of recycled products [7]). The rejected material from the recycling processes and the Residual Unsorted Waste (RUW) have to be treated before being disposed into landfill or burned in an incinerator, according to the Italian law LD 211/2015 art. 48.

For this reasons, in many countries, the Mechanical Biological Treatment (MBT) plants became important elements of the ISWM system [8], [9]. These plants undertake a series of operations on the RUW aimed to: (i) increase the calorific value of the main outlet stream by separating the light and dry fraction (paper, plastic, textiles, etc.) from the wet one (organic matter)[10]; (ii) recover the ferrous and non-ferrous metal to be devolved to recycling plants [11]; (iii) stabilize the organic part before the final disposal [12][13]; (iv) reduce the volume of waste to be disposed in landfill [14], [15]. Currently in Italy, there are 130 MBT plants, which treat more than 10 million of MSW per year, 90% of which are RUW [16]. There are different types of MBT plants depending on the type of flow repartition: 'single-flow', 'separated-flow' and 'mechanical'[17], [18]. In most cases, the main final product is the Refused Derived Fuel (RDF) (or Solid Recovered Fuel, SRF, according to the new nomenclature), whose utilization in Italy is regulated by the Law D.L. 205/2010 in accordance with the standard UNI EN 15359 [19], [20]. RDF can only be used in incinerators, cement factories or thermal power plants of more than 50 MW, otherwise it is disposed in landfill. The RDF can be 'fluff', 'densified' or 'dust', depending on the procedure that is used for its production [21].

In the literature there are various examples of works focused on modelling and analysis of MBT plants. A Material Flow Analysis (MFA) is conducted in [22] with the goal of valuating the effectiveness while removing hazardous substances. The influence of input waste and processing technologies on RDF characteristics are studied in [14]. Experimental analyses are conducted with the aim to show the environmental advantage of insert a MBT plant before landfill [13]. Mass, energy and material balances are validated with laboratory analysis in [23], which compares different types of wastes. In [11], a Life Cycle Assessment (LCA) approach is used for evaluating the energy and environmental performance of a MBT plant producing RDF for cement kiln co-combustion. Results of a LCA are also presented in [12], comparing eight European MBT plants.

Since these systems involve material and non-material streams, the use of exergy analysis coupled with economic balance (Exergoeconomics) appears particularly useful in this framework. In fact, exergy (e.g. the maximum useful work obtainable from a system when it is taken from its given state to the thermodynamic equilibrium with the environment, by only interacting with the environment [24]) is used as a rational basis for comparing flows of different nature [25]. In a waste treatment plant, mechanical processes involving electric energy consumption are performed. According to the Second Law of Thermodynamics, the sources of irreversibility of the system are linked to material losses and exergy destruction. Exergy based performance indicators provide a measure of the distribution of the irreversibility trough the equipment and so of the recovery degree of exergy potential [26]. Dewulf et al. [27] used exergy analysis to perform a quantitative assessment of solid waste treatment systems in the industrial ecology perspective, showing that the exergy concept contributes to a better assessment of sustainability of technology with respect to resource management. Exergoeconomics has also been applied by Valero et al. [28] to Industrial Ecology issues such as identification of integration possibilities and efficiency improvement, quantification of benefits obtained by integration, or determination of fair prices based on physical roots. Currently, no examples of Exergoeconomic analysis applied to specific waste treatment plants (such as MBT plant) are found in literature.

The present work contains a second relevant novelty. In real working conditions, the operation of these kind of systems is strongly influenced by social, political and economic conditions, which entail a high degree of uncertainty. The uncertain factors can be external (site-dependent) or internal. External factors are the structure of collection system and the degree of selective collection, which influence the waste composition, and the market demand of end products that affects their production. Internal factors are the structure of each treatment chain or malfunctions in equipment, which lead to variable energy consumption. Some example of inclusion of uncertainty in the analysis of ISWM systems are present in literature [29], [30]. In this case, stochastic and probabilistic tools are adopted for generating simulation scenarios, such as crude Monte Carlo method (eventually coupled with inversion method) for sampling from uniform or normal probability distribution.

In summary, the aim of this work is to evaluate the performance of the MBT plant under an Exergoeconomic perspective, considering the influence of aleatory variations of external and internal operating parameters and so reproducing the variety of operating conditions that can be faced.

2. Model assumptions and methodology

The value of Global Selective Collection SC_{gl} is defined as the percentage of MSW that is separated and collected [16]. This is the weighted average of the mass flow of the separated material streams m_i (namely paper, plastic, organic matter, wood, metal, glass and textile), where the weight is the degree of selective collection of the single stream SC_i (Eq. 1). The relation between the Total Unsorted Waste (TUW) and the RUW (the unsorted waste before and after the selective collection, respectively) and the value of SC_{gl} are expressed by Equation 2.

$$\%SC_{gl} = \frac{\sum_i SC_i \cdot m_i}{TUW} \tag{1}$$

$$RUW = \left(1 - \%SC_{gl}\right) \cdot TUW \tag{2}$$

The following section reports the description of the steps for modelling and simulating the MBT plant, including the parameters used for the evaluation. The model is validated with data declared by real MBT plants, by comparing the values of LHV and Moisture Content (MC) of RDF. All the modelling and simulation are performed in Matlab environment.

2.1 Mass balance

Since the relation between the inputs and outputs of each equipment is linear (no chemical or nuclear reactions occur), mass balances are performed using transfer matrices. For the MBT plant, the Recovery Factor Transfer Function (RFTF) matrix [31] introduced by Diaz [32] is used. According to this methodology, transfer coefficients are assigned to each equipment of the treatment chain for each inlet material stream, for the wet and the dry part respectively. Equation 3 expresses the relation between the input and output flow of the i-th material stream through the j-th component of the chain. The reference process chains are the ones depicted in Figure 1.

$$m_{i_{out}} = m_{i_{in}} \cdot RFTF(j) \tag{3}$$

The RFTF matrix used in this work is shown in Table 1. In order to perform the calculation, some assumptions are made on the repartition of the inlet material streams: Organic Matter (OM) stream is composed by organic waste and garden trimmings; Other Plastics (OP) stream includes PVC and hard plastics; diapers are divided in 50% of organic matter, 35.5% of cellulose (paper) and 14.5% of plastic [33]; Other Inorganics (OI) include mostly inert and a small percentage of batteries and dangerous waste. Wet and dry part and ultimate analysis are calculated according to the values in Table 2.

Table 1
RFTF matrix factors, elaborated by the authors based on [11], [33], [34]

j-th component		*i-th material stream*										
		Paper	Plastic	OP	OM	Wood	Leather	NF metal	Ferrous metal	Glass	Textile	OI
Storage	Dry	1	1	1	1	1	1	1	1	1	1	1
	Moisture	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Shredder	Dry	1	1	1	1	1	1	1	1	1	1	1
	Moisture	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98
Magnetic separator	Dry	0.98	0.98	0.98	0.95	0.98	0.98	1	0.2	1	0.98	0.95
	Moisture	0.98	0.98	0.98	0.95	0.98	0.98	1	0.2	1	0.98	0.95
Eddy current separator	Dry	0.98	0.98	0.98	0.98	0.98	0.98	0.1	1	1	0.98	0.98
	Moisture	0.98	0.98	0.98	0.98	0.98	0.98	0.1	1	1	0.98	0.98
Preliminary screening	Dry	0.785	0.69	0.69	0.166	0.73	0.73	0.52	0.52	0.198	0.73	0.468
	Moisture	0.785	0.69	0.69	0.166	0.73	0.73	0.52	0.52	0.198	0.73	0.468
Fine screening	Dry	0.97	0.96	0.96	0.46	0.96	0.96	0.91	0.91	0.08	0.96	0.7
	Moisture	0.97	0.96	0.96	0.46	0.96	0.96	0.91	0.91	0.08	0.96	0.7
Air classifier -shredded refuse	Dry	0.98	0.98	0.98	0.7	0.98	0.98	0.5	0.1	0.7	0.98	0.2
	Moisture	0.882	0.882	0.882	0.63	0.882	0.882	0.45	0.09	0.43	0.882	0.18
Air classifier -un-shredded refuse	Dry	0.98	0.98	0.98	0.4	0.98	0.98	0.5	0.1	0.02	0.98	0.15
	Moisture	0.882	0.882	0.882	0.36	0.882	0.882	0.45	0.09	0.018	0.882	0.135
Near Infrared Removal (NIR)	Dry	1	0.94	0.01	1	1	1	1	1	1	1	0.7
	Moisture	1	0.94	0.01	1	1	1	1	1	1	1	0.7
Pelletizer	Dry	1	1	1	1	1	1	1	1	1	1	1
	Moisture	1	1	1	1	1	1	1	1	1	1	1

Table 2
Ultimate analysis of RUW streams, elaborated by the authors based on [34]

		% by mass, dry basis						
	%MC	C	H	O	N	S	Cl	Ash
Paper	16.7	43.3	5.8	44.2	0.3	0.2	0.2	6
Plastics	6.5	59.2	7.1	22.5	-	-	1.3	9.8
OP	2	54.9	6.6	20.8	-	-	8.5	9.2
OM	69.6	47.7	6.4	37.4	2.6	0.4	0.5	5
Wood	48	45.9	5.9	37.9	3.4	0.3	0.3	6.3
Leather	10	59.8	7.9	11.5	10	0.4	0.4	10
NF Metal	3.7	4.5	0.6	4.3	0.1	-	-	90.5
Ferrous metal	2	4.5	0.6	4.3	0.1	-	-	90.5
Glass	2	0.5	0.1	0.4	0.1	-	-	98.9
Textile	10	47.8	6.4	39.8	2.2	0.2	0.4	3.2
OI	8	-	-	-	-	-	-	-

2.2 Energy balance

In a MBT plant, the main energy consumption is the electric one. According to literature review, a range of energy consumption (kWh/Mg) is indicated for each equipment. The variation are due to the diversity in the inlet material characteristics (i.e. sizing, moisture content, density, mass flow) or to random malfunctions [35]. Table 3 resumes the energy consumptions of the equipment included in the treatment chains considered in this work.

Table 3
Elaborated by the authors based on [12], [32], [35]–[37] and data declared by plant managers

Equipment	**Description**	**Energy consumption** Range (kWh/Mg)	Chosen value (kWh/Mg)	**Cost(1)** (k€)
Primary shredding	First shredding after the delivery of the material. The energy consumption depends from the dimensional reduction following the Kick's Law $E = C \cdot \ln(\frac{F_0}{X_0})$ with F_0=170mm and X_0=80mm and C=8.22÷16.44	6.2 -12.4	9.3	51.9
Secondary shredding	The air-classified light fraction requires more energy for shredding than the mixed waste	15 - 25	20	51.9
Magnetic separator	Removal of ferrous metal. The energy consumption is due to the movement system of the conveyor belt.	0.2 - 2.4	1.3	36.15
Eddy current separator	Removal of non-ferrous metal.	0.7 - 1.2	0.8	7.23
Pre-trommel	First screening for the primary separation of the organic wet fraction from the light one; the size of the screening is generally 80 mm. Energy consumption is due to the movement of the grid.	0.7 - 1.5	1.1	51.65
Fine screening	Secondary screening from removal of fines and residual organic part after the shredding. The size of the screening can be 50 mm or less.	0.7 - 1	0.8	51.65
Air classifier	Light fraction (paper, plastic, textile) separation. The specific energy consumption depends from the inlet moisture content and increases if a dust collection system is included.	1 - 4.1	3	41.3
Pelletizer	Increase in final product density and quality. The energy consumption increases when the production and the moisture content decreases	25 - 35	30	206.58
NIR	Removal of hard plastic (PVC) trough optical separation with an infrared generator.	3.3 - 6.1	4.7	50
'Rocket' shredding	Hard shredding with hammer mill. High energy consumption and maintenance but good quality of RDF.	33.6 - 62.4	48	51.9
Auxiliary				
Conveyor/Raising	Empirical relation for a belt length L=20m and a raising height H=2m.		6.722e-03/ 5.46e-03	15.49
Fan	It is associated to storage and air classifier.		3.8	
Press	It can be included at the end of the chain or between the first and second treatment section.		1.5	

$^{(1)}$The costs refer to a plant capacity of 5 tons/hour

For calculating the Lower Heating Value (LHV) of the inlet material and the outlet fuel, the Mendeliev equation is adopted (Eq. 4) [38], where the coefficient of Carbon, Hydrogen, Oxygen, Sulphur (C, H, O, S) and the MC are on wet basis.

$$LHV\left[\frac{kJ}{kg}\right] = 4.187 \cdot [81C + 300H - 26(O - S) - 6(9H + MC) \tag{4}$$

2.3. Exergy and cost balance

The exergy of the mixed waste $\dot{B}_{RUW_{in}}$ (kW) is evaluated by considering the organic, inorganic and water content separately. The organic part includes the streams that contains mainly carbon (C) and hydrogen (H), namely paper, organic matter, wood, leather, plastics and textiles. The chemical exergy content of these materials b_{ch_i} is calculated using the Equation 5 [39], where φ is the coefficient of correction of LHV, proposed by Szargut [24] and depending on the O/C ratio, and while W ad S are the water and sulphur content (%). Regarding the inorganic part, the exergy of pure iron and aluminium is assumed respectively for ferrous and non ferrous metal; the exergy of glass is calculated considering the solid mixing of the glass components (1.5% Al_2O_3, 10.8% CaO, 13.2% Na_2O,73.3% SiO_2) [40]; the exergy of inert material can be disregarded, as demonstrated by [41]. For the water W, only the chemical exergy ($b_{ch_{wat}}$) is considered, since ambient temperature (T_0) and pressure (p_0) are assumed. All the values of LHV and exergy of the material stream and the relative φ coefficient are reported in Table 4.

$$b_{ch_i} = \varphi \cdot (LHV_i + 2442W) + b_{ch_{wat}} \cdot W + 9683 \cdot S \tag{5}$$

Furthermore, an exergy cost balance [42] is written for each equipment of the chain (Eq. 6). All terms are expressed in €/sec.

$$c_{RUW_{in}}\dot{B}_{RUW_{in}} + c_{el}\dot{B}_{el} + \dot{C}_{eq} = c_{rej}\dot{B}_{rej} + c_{pr}\dot{B}_{pr} \tag{6}$$

The cost of electricity c_{el} (€/kWh) is fixed to the one of Italian market (0.052 euro/kWh [43]). If we consider the MBT plant only, the inlet cost of RUW $c_{RUW_{in}}$ is negative since it corresponds to the disposal fee paid from the municipalities, assumed as 0.067 euro/kg [16]. The cost of the rejects c_{rej} is supposed to be the same, but it is positive for the plant [44]. The RDF and recovered metal are considered as the two products of the plant. An additional equation is written for the magnetic separator in order to find the cost of the products c_{pr}. According to the equality method, the same unit exergy cost is assigned to all products, therefore the additional equation is $c_{pr} = c_{met} = c_{RDF}$. Equation 7 is utilized for calculating the cost rate of the equipment $\dot{C}_{eq}$. The operation and maintenance factor $f_{O\&M}$ is 10% of the global cost, the actualization factor f_a is given by Eq. 8 considering an interest rate i of 7.5% and a capital recovery period N of 10 years is assumed [45]. The annual equivalent hours h_{year} are evaluated considering 8 working hours per day for 6 days a week. The actual costs of the equipment are reported in Table 3 for a reference plant capacity of 5 ton/hours.

$$\dot{C}_{eq} = \frac{C_{eq} f_{O\&M} f_a}{3600 \times 7800} \tag{7}$$

$$f_a = \frac{i}{1-(1+i)^{-N}} \tag{8}$$

Table 4
Chemical exergy and φ coefficient for material stream, elaborated basing on [24], [34]

Material Stream	LHV_i (kJ/kg)	Exergy content b_{ch_i} (kJ/kg)	φ
Organic part			
Paper	15815	19278.3	$\frac{1.044+0.016\left(\frac{H}{C}\right)-0.3493\left(\frac{O}{C}\right)\cdot[1+0.0531\left(\frac{H}{C}\right)]+0.0493}{1-0.4124\left(\frac{O}{C}\right)}$
OM	4175	6750.1	
Leather	18515	20148.9	
Textile	17445	20375	
Plastic	32000	34800.6	$1.0437+0.014\left(\frac{H}{C}\right)+0.0968\left(\frac{O}{C}\right)+0.0467\left(\frac{N}{C}\right)$
OP	32000	34682.1	
Wood	15444	18770.8	$\frac{1.0412+0.216\left(\frac{H}{C}\right)-0.2499\left(\frac{O}{C}\right)\cdot[1+0.7884\left(\frac{H}{C}\right)]+0.045}{1-0.3035\left(\frac{O}{C}\right)}$
Inorganic part			
Ferrous metal (Fe)		6740	
Non-ferrous metal (Al)		32926	
Glass		885.7	
Water		50	

2.4. Model validation

The model is validated by testing the RFTF matrix with some real MBT chain structures and comparing the characteristics (MC and LHV) of the final RDF with the data declared by the plants. Results of the validation are reported in Table 5. RUW composition used for the validation is calculated from the values reported in Table 6, according to waste gravimetric composition of Torino metropolitan city. The discrepancies in RDF MC and LHV from the real plants data are reasonably due to the fact that the real RUW composition entering each plant is different from the one used for the validation. The exact waste composition is not declared and is difficult to predict, since it depends from aleatory factors and no average values are given. For this reason, percentage differences until 10% are accepted as good values for the validation.

Table 5
Results of the validation with different Italian MBT chains: I) Pinerolo plant, II) 'A2A ambiente' plant, III) Sommariva del Bosco plant

	RDF MC (%)	RDF LHV (kJ/kg)
MBT plant-I	14.5	16036
Model	15.3	15716
Difference (%)	+5.6	-1.9
MBT plant-II	18	16636
Model	17.2	16025
Difference (%)	-4.4	-3.6
MBT plant-III	14.9	21212
Model	13.3	21080
Difference (%)	-10.7	-0.62

Table 6
Base case scenario according to the UW gravimetric composition of the city of Torino (IT) [46] (w.b.: wet basis)

Material Stream	Gravimetric composition of TUW %wg (w.b)	SC_i *(%)* w.b.	Internal repartition of SC (%) w.b.
Paper	26.97	52.6	27.45
Plastics	17.16	50.27	16.7
OP	0.94	0	0
OM	33.8	58.4	38.2
Wood	6.13	73.46	8.7
Leather	0.26	0	0
NF Metal	1.08	27.84	0.585
Ferrous metal	1.49	20.19	0.585
Glass	6.29	56.29	6.85
Textile	3.05	15.97	0.94
OI	2.8	0	0

2.5. Sensitivity analysis

In order to show the effect of the equipment position on efficiency, two different structures of chain are considered, based on real plants layout, as reported in Figure 1. The main differences consist in the presence of the pelletizer and the NIR, since the final product is utilized in two different plants (an incinerator in case A and a cement factory in case B). The auxiliary energy consumption (Table 7) is calculated considering a proper number of conveyor belts and raisings according to the number of equipment. A fan is associated to each Air Classifier and Storage. In addition, a press is collocated after the pelletizer in chain A.

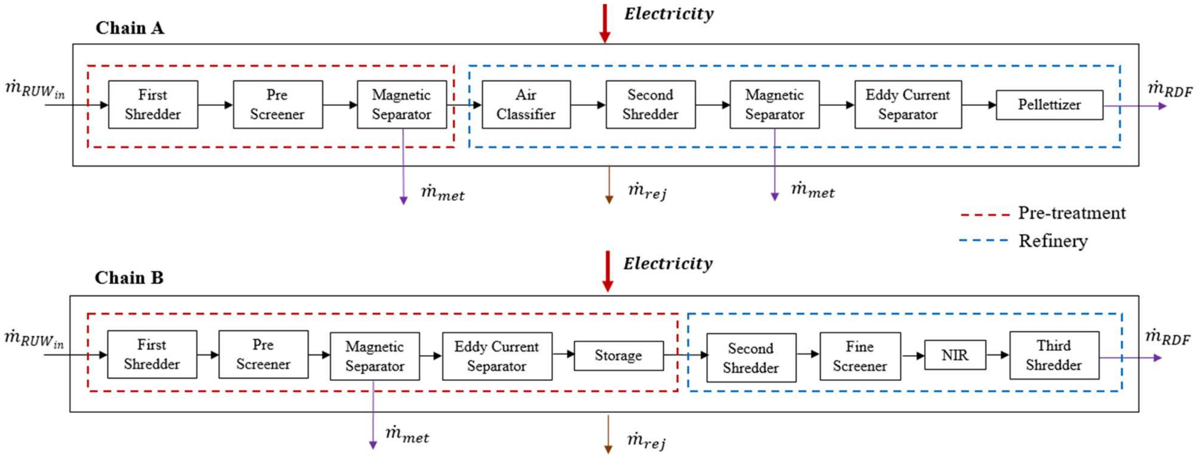

Figure 1
Different chain structures analysed in the work

Table 7
Auxiliary consumption calculated for the two chains, by calculation from [35]

	Auxiliary consumption (kWh/Mg)	
	Chain A	**Chain B**
Conveyor belts	0.087	0.074
Raisings	0.01	0.01
Fan	3.8	3.8
Press	3	-
Total	6.897	3.884

A sensitivity analysis is performed in order to evaluate the influence of the main external and internal parameters. The values of TUW composition, SC_i percentage and SC internal repartition for the base case scenario are reported in Table 6. The SC_i of paper, plastic and organic matter are varied linearly in a range between -30/+30% with respect to the base case. The global energy consumption is varied between the minimum and maximum values found in the literature (Table 3) (the auxiliary consumption is assumed constant).

2.6. External uncertainties

External uncertainties are associated to variations in inlet waste composition, due to fluctuations in selective collection. Uncertainties are included by means of random sampling on uniform distributions of SC_i values using a crude Monte Carlo simulation, which is based on the random generation of a high number of values n. The ranges of variation of SC_i are defined after an extent review of data available in the Italian scenario. The minimum and maximum values are about the same obtained by varying SC_i of ±50%. According to each random generated scenario, the percentage composition of RUW as well as the internal repartition of the separated waste are calculated. The percentage composition of the UW before the collection is assumed as constant. The output parameters are evaluated according to their probability distribution, considering the mean value μ and the Relative Standard Deviation (%RStD) (Eq. 9-11) [47].

$$\mu = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{9}$$

$$\sigma = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n} |x_i - \mu|^2} \tag{10}$$

$$\text{RStD (\%)} = \frac{\sigma}{|\mu|} \times 100 \tag{11}$$

The μ value represents the central tendency of the n generated values x_i, while the RStD is the ratio between the Standard Deviation σ and μ and it gives a measure of the dispersion of values around μ and so of the sensibility to the uncertainty. The distribution of output values can be discretized by dividing the range of existence in a number of equidistant k intervals each one containing n_k values. In this way, the relative frequency or probability p_i associated to the values in the k-th range is defined as in Eq.12. This is not an absolute value, since it depends on the arbitrary choice of n and k, but it can be useful at the time of comparing different distributions of the same parameter.

$$p_i = \frac{n_k}{n} \tag{12}$$

2.7. Internal uncertainties

The internal uncertainties are associated with the energy consumption of the equipment, which can present an aleatory behaviour due to the characteristics of the inlet material (sizing, moisture content, density, mass flow) or random malfunctions. According to the ranges of electric consumption indicated in Table 3, a normal probability distribution is supposed for each equipment consumption. In order to simulate the plant considering the uncertain internal factors, a procedure for sampling from the normal distribution is implemented. First, a discrete probability distribution following the normal one is created, according to the percentage repartition of the standard curve [47], and the μ value and RStD are calculated. These values are then used to simulate the Cumulative Distribution Function (CDF) of a continuous normal distribution, which is sampled using the Inversion method (Eq. 13-14) with a Monte Carlo simulation [48]. The procedure consists in generating an high number of values U between 0 and 1 and finding the correspondent value X on the CFD curve. Even in this case, the simulation is performed considering the two different chain structures, by fixing the inlet composition of the waste to the base case.

$$F(X) = P\{X < x\},\ \textit{CDF of x distribution values} \tag{13}$$

$$U \in \{0,1\},\ \ X = F^{-1}(U) \tag{14}$$

2.8. Evaluation parameters

In order to evaluate the efficiency of the treatment chains with the variation of external and internal variables, some evaluation parameters are considered. First of all, the Yield (%) of RDF is calculated as the ratio between the outlet RDF and the inlet RUW flows (Eq.15), being a measure of the global material recovery [22]. The quality of RDF is expressed by its MC (%), LHV (kJ/kg) and exergy content $B_{ch_{RDF}}$ (kJ/kg).

$$Yield\ (\%) = \frac{RDF\ flow\ rate}{RUW\ flow\ rate} \tag{15}$$

The Global Energy Consumption (GEC), namely the direct sum of the consumption of every equipment plus that of auxiliaries, is calculated to account for the influence of internal uncertainties. According to the exergy balances, Second Law Efficiency η_{ex} (Eq.16) is evaluated for the entire plant: the exergy of the two products is compared with the global exergy invested in the plant, namely the exergy of RUW and the electric energy.

In order to allocate the irreversibility ψ_{I_j} due to material and energy losses, lack of efficiency δ_j (Eq.17) and specific irreversibility y_j of j-th component (Eq.18) are calculated for each equipment. In case of δ_j the exergy destroyed in each equipment is related with the global exergy consumption, while in y_j with the exergy of the product of the same equipment [49].

$$\eta_{ex} = \frac{\dot{B}_{RDF} + \dot{B}_{met}}{\dot{B}_{RUW_{in}} + \dot{B}_{el}} \tag{16}$$

$$\delta_j = \frac{\psi_{I_j}}{\dot{B}_{RUW_{in}} + \dot{B}_{el}} \tag{17}$$

$$y_j = \frac{\psi_{I_j}}{\dot{B}_{pr_j}} \tag{18}$$

3. Results

3.1 Sensitivity analysis

3.1.1 Effect of SC and energy consumption

Table 8 reports the results of the sensitivity analysis performed on the two treatment chains. The RDF unit exergy cost c_{RDF} as well as the exergy efficiency refer to a scenario with recovery of ferrous metals. The metal unit exergy cost c_{met} of the chain A refers to the second Magnetic Separator; the value associated to the first Magnetic Separator is the same of the chain B.

With regard to the effect of the *SC* parameters, the behaviour of the output parameters in the variation range (±30%) is linear. RDF Yield presents the highest variations when SC of paper is varied (+11/-15% for chain A and +14/-19% for chain B). The yield increases (+14%) with an increment in SC of organic matter, since this implies a major percentage of plastic and paper in the inlet RUW stream. The LHV of RDF has an increment (+5% for chain A and +3.6% for chain B) only for higher values of SC of paper. In the other cases when the quantity of plastic and organic matter diminishes, the reduction of MC is not compensated by an increase in carbon content and so the LHV decreases. The unit exergy cost of the products and the exergy efficiency are linked in the sense that a decrease in η_{ex} leads to a higher exergy cost for producing the same amount of products, which is reflected in an increase of the unit exergy costs. The major variations are associated to the degree of SC of plastic, both for c_{RDF} (-13/+24%) and c_{met} (-17/+15.8%). The unit exergy cost of ferrous metal depends on the position of the magnetic separator, as expected; c_{met} increases of 9% when the magnetic separator is the sixth position instead of third, because it is affected by all the exergy cost (in terms of exergy invested and destructed) until that equipment. The exergy efficiency behaviour depends on the combined effect of Yield and LHV of RDF; decreasing LHV can lead to increment in η_{ex}, only if it is balanced by a consistent increase in Yield, as in the case of variation of SC of organic matter.

A comparison between the two chains shows that the structure B presents a lower Yield (-7%) and exergy efficiency (-8%) with respect to A, while the RDF unit exergy cost is higher (+7%).

The energy consumption has no influence on the Yield and the LHV of RDF. A variation between the minimum and maximum value leads to minor fluctuations from the base case, with percentage differences in the order of 1% for cost of products and exergy efficiency. There are no significant differences between the responses of the two chain. In general, it is evident that the influence of the internal variable is definitely lower than the external one, with percentage differences more than 90% lower, at least in the considered variation range.

Table 8
Results from sensitivity analysis

		SC paper		*SC* plastic		*SC* organic		Energy consumption		Base case values
		-30/+30%	%Diff	-30/+30%	%Diff	-30/+30%	%Diff	Min/Max	%Diff	
Yield (%)	A	43.9/33.7	+11/-15	41.8/36.9	+5.5/-7	36.7/45.1	-7.3/+14	-	-	39.6
	B	40.9/29.1	+14/-19	38.1/33.3	+6/-7	33.2/41.1	-7.5/+14.5			35.9
LHV (kJ/kg)	A	14933/16337	-3.5/+5	16643/13846	+7.5/-10.5	16199/14362	+4.7/-7.2	-	-	15473
	B	15113/16295	-3.9/+3.6	16887/14095	+7.4/-10.4	16521/14524	+5/-7.6			15728
c_{RDF} (10^{-4} €/kJ$_{ex}$)	A	0.087/0.102	-5.4/+10.8	0.08/0.114	-13/+24	0.095/0.089	+3.3/-3.3	0.091/0.093	-1.1/+1.1	0.092
	B	0.092/0.113	-7/+14	0.086/0.123	-13/+24	0.102/0.096	+3/-3	0.098/0.101	-1/+2	0.099
c_{met} (10^{-4} €/kJ$_{ex}$)	A	0.08/0.093	-2.4/+13.4	0.074/0.104	-17/+15.8	0.087/0.081	+6/-1.2	0.084/0.086	-1.2/+1.2	0.085
	B	0.074/0.085	-2.6/+11.8	0.068/0.095	-12.8/+18	0.081/0.074	+3.8/-5	0.078/0.079	0/+1.3	0.078
Exergy efficiency (%)	A	62/57.3	+3/-4.8	60.8/59.1	+1/-1.8	59.3/61.7	-1.5/+2.5	60.5/59.9	+0.5/-0.3	60.2
	B	58/51.6	+5/-6.5	56/53.8	+1.4/-1.8	54.6/56.3	-1.1/+2	55.6/54.8	+0.7/-0.7	55.2

3.1.2 Irreversibility

The distribution of irreversibility y_j among the equipment and the lack of efficiency δ_j due to material and energy losses are shown in Figure 2 and 3 respectively. Material losses are the primary source of irreversibility and are mainly concentrated in the pre-screening phase; it means that an average of 70% of the global input exergy (75% for chain A and 65% for chain B) is lost in this equipment. The metal separation and fine screening have similar values of y_j for both the structures, in the order between 5 and 10%, while the contribution of the shredding is less than 1%. The NIR separator has an important effect on chain B exergy losses (12%), higher than air classifier for chain A (6%). The distribution of the lack of efficiency confirmed this interpretation, underlining the differences between the energy and the material losses. Figure 3 shows that some equipment (shredder, pelletizer and storage) are almost only energy destructive.

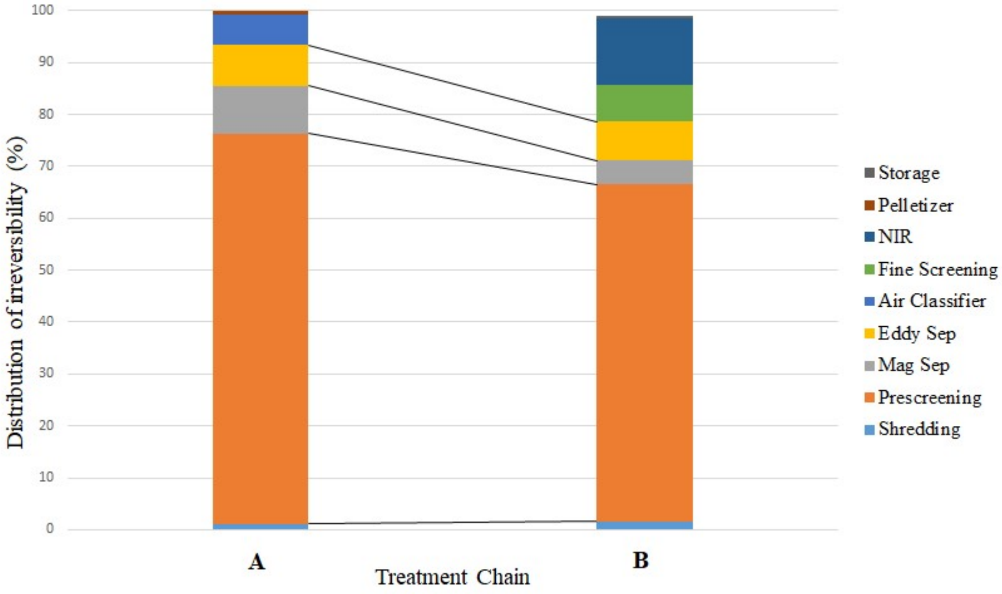

Figure 2- Distribution of irreversibility among the equipment: comparison between the two chains

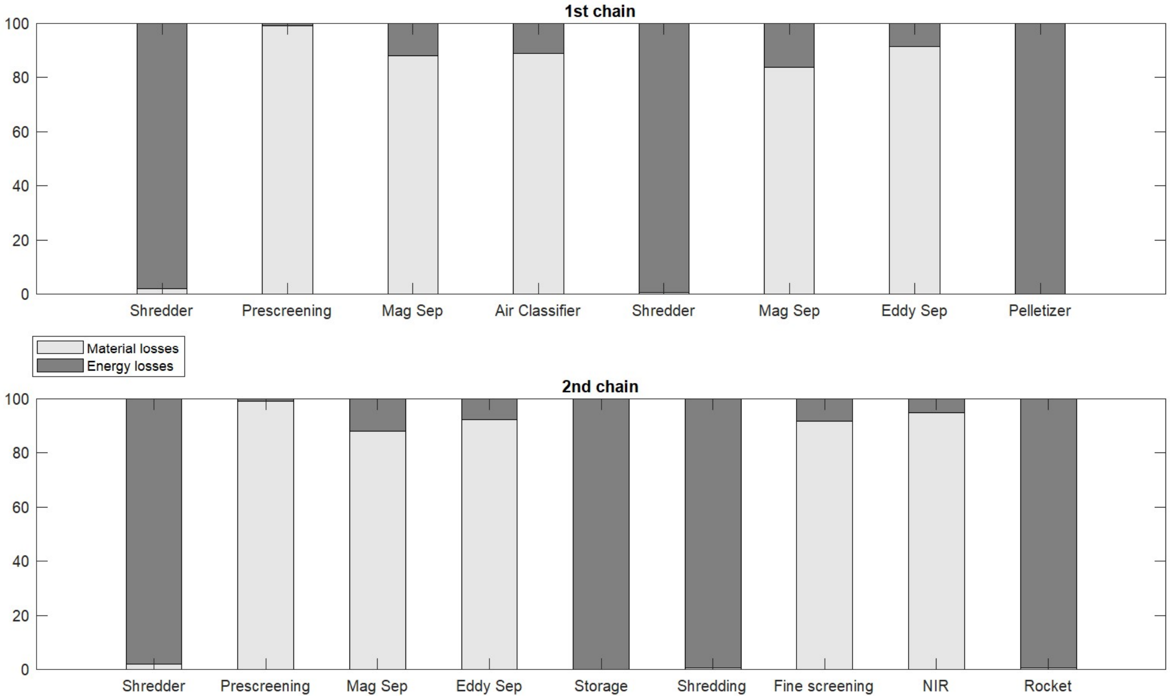

Figure 3- Lack of efficiency due to material and energy losses: comparison between the two chains

3.2 The effects of uncertainties

3.2.1 External uncertainties

The results of the random sampling using the Monte Carlo method are reported in Table 9, which contains the μ values and RStD of the output parameters. First of all, it is interesting to notice the μ value of SC_{gl}, since it represents the most probable value obtained by a random variation and combination of the values of SC_i. The SC_{gl} values follow the behaviour of a normal probability distribution (Figure 4), since it is the weighted sum of a number of independent random variables, each having a uniform distribution. The resulted theoretical probability distribution is the Irwin-Hall distribution with n=8 random variables [50].

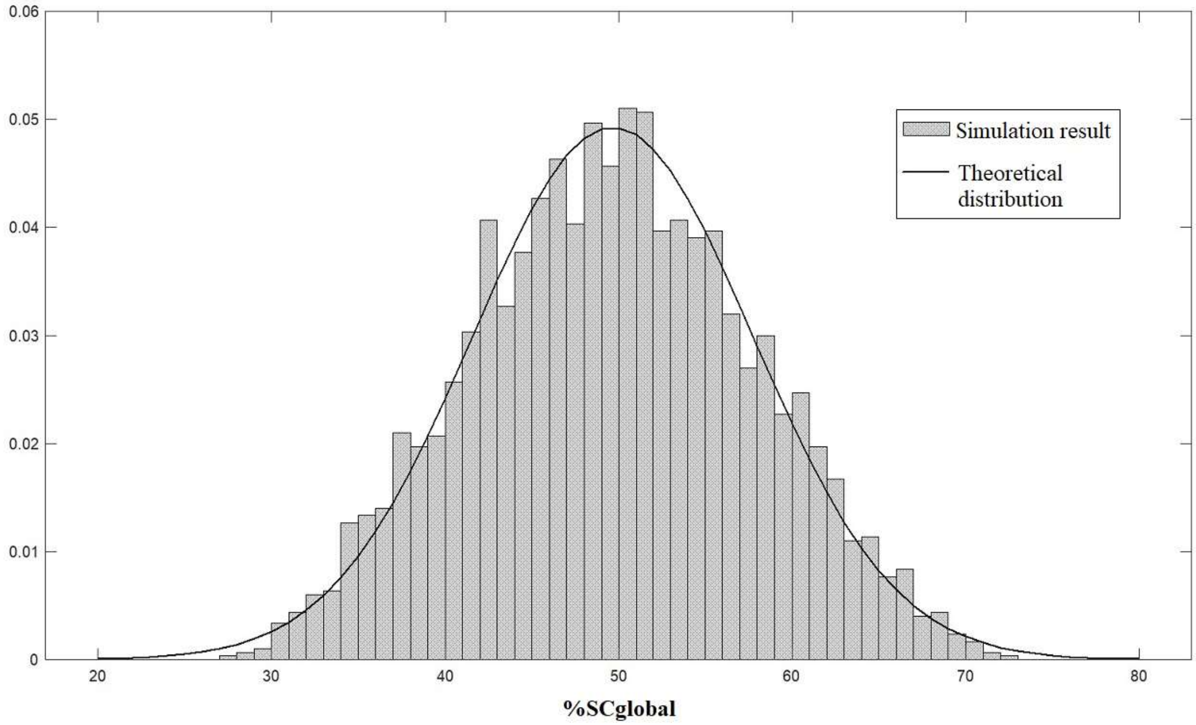

Figure 3- SC_{gl} distribution resulting from Monte Carlo simulation on waste composition

Regarding the evaluation parameters, the unit exergy cost of products is the most influenced by the uncertainties, showing an RStD of about 16%, while the exergy efficiency is the less affected (about 3%). As a general consideration, the dispersion of values around μ diminishes for the output parameters (Yield, LHV of RDF, exergy efficiency and cost of products). It means that the values of RStD of these parameters are considerably lower than the fluctuations of the input random variable (in this case the SC_i values and the energy consumption). This is an effect of the transformation operated by the treatment process, which tends to homogenise the inlet material.

A comparison between the two chains shows that Chain A presents better performances with respect to Chain B, as already noted in the sensitivity analysis. The Yield has higher values (+7.7%), as well as the LHV of RDF (+0.2%) and the exergy efficiency (+8.5), which leads to lower RDF exergy costs (-7.8%). Besides, Chain B is more sensitive to the uncertainties, as demonstrated by the values of RStD, which are from 1.7% to 39% higher than Chain A, depending from the parameter.

The trend of the probability distributions of evaluation parameters after Monte Carlo simulation on waste composition is graphically shown in Figure 4. The Yield presents a behaviour similar to the normal one, while the unit exergy cost and exergy efficiency are markedly not centred, following approximately an inverse Weibull distribution more than a normal one.

Table 9

Mean values μ and standard deviations of evaluation parameters resulting by uncertainty analysis

	External uncertainties				**Internal uncertainties**			
	μ		RStD (%)		μ		RStD (%)	
	A	B	A	B	A	B	A	B
SC_{gl} (%)	49.7		16.3		-	-	-	-
Yield (%)	42	39	11.8	13.3	-	-	-	-
LHV (kJ/kg)	15462	15432	5.8	5.9	-	-	-	-
RDF Unit Exergy cost (10^{-4} €/kJ_{ex})	0.089	0.096	16.1	16.8	0.086	0.092	0.09	0.27
Metal unit exergy cost (10^{-4} €/kJ_{ex})	0.082	0.076	15.8	15.5	0.08	0.074	0.02	0.02
Exergy efficiency (%)	60.8	56	2.8	3.9	62	55.2	0.07	0.14
Global energy consumption (kWh/Mg)	-	-	-	-	73.3	93.8	3.7	5.5

3.2.2 Internal uncertainties

With regard to the internal uncertainties, the only evaluation parameters affected by the random variation of energy consumption are the exergy efficiency, the unit exergy costs of products and the GEC. As it can be seen in Table 9, the RStD of c_{RDF} and c_{met} and of η_{ex} is about two orders of magnitude lower than the one of the GEC. Besides, a comparison with Chain A shows that the RStD values are more generally lower for chain B and about 90% lower with respect to the external uncertainties ones. This result confirms the small impact of energy consumption of the equipment on the global performance of the system. Besides, as in the case of external uncertainties, it shows that the effect of fluctuations of energy consumption are absorbed and reduced within the system. As expected, the discrete probability distributions of the values follow the behaviour of the normal distributions, as can be seen in Figure 5. This is a consequence of the fact that the input variable varies in the assigned range according to a normal probability distribution.

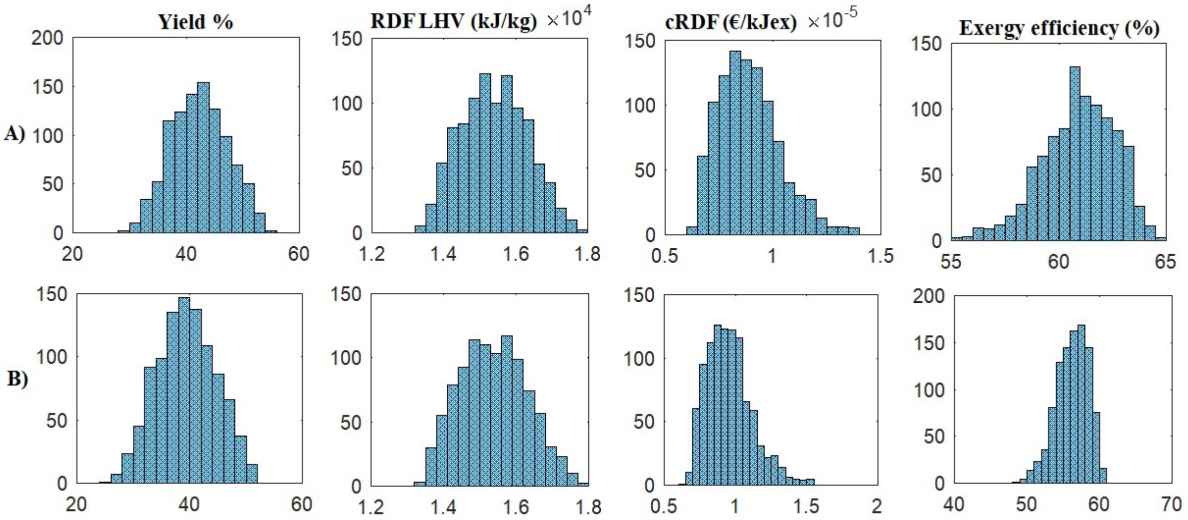

Figure 4- Probability distributions of evaluation parameters after Monte Carlo simulation on waste composition

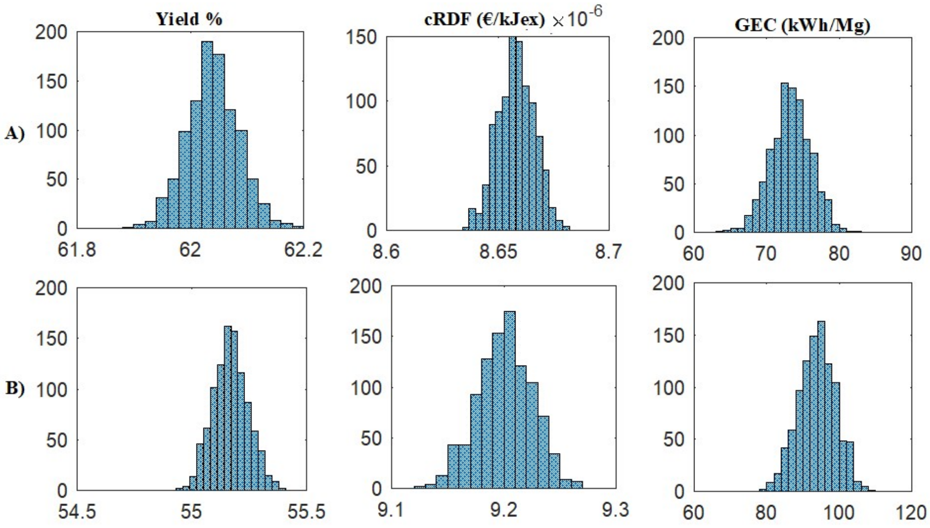

Figure 5- Probability distributions of evaluation parameters after Monte Carlo simulation on energy consumption

3.2.3 Combined effects

In real working conditions, the system will be influenced at the same time by external and internal factors. For this reason, the combined effect is analysed and the results are reported in Figure 6. The predominant influence of the external variables is even more evident, since the mean values of η_{ex} and c_{RDF} (red line in Fig.6) are very close to the ones obtained by performing the Monte Carlo simulation on waste composition only (see Table 9). Regarding the discrete probability distributions, it is interesting to notice that only for the η_{ex} of chain A, the p_i of the μ value is in the range of maximum probability. For the other parameters, the ranges are not the same, as can be seen by the values reported in Table 10.

Table 10
Comparison of the probability of the mean value with the range of maximum probability in case of combined effects

	Chain A		Chain B	
	η_{ex}	c_{RDF}	η_{ex}	c_{RDF}
μ value p_i (%)	12.04	11.88	10.94	11.87
Maximum p_i (%)	12.04	12.28	12.28	12.94

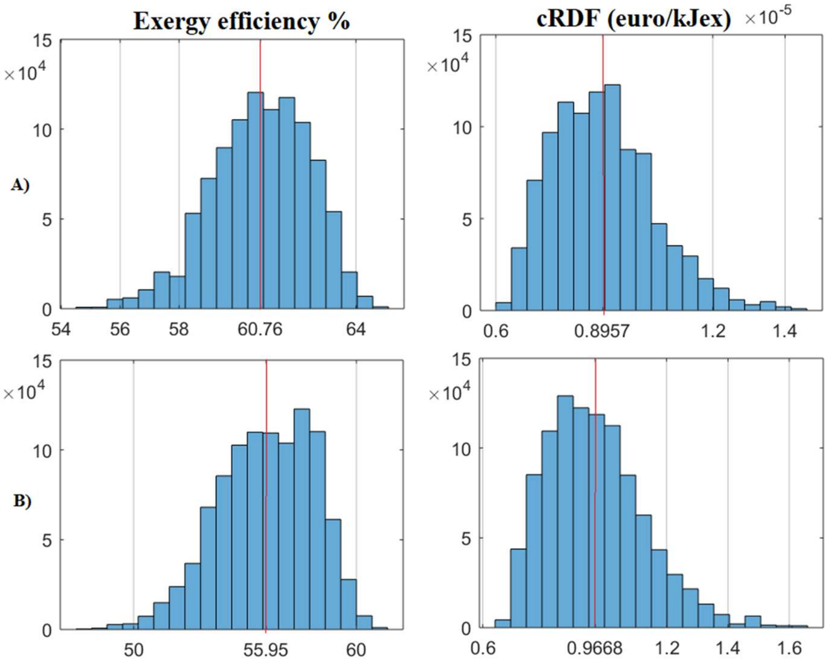

Figure 6- Probability distributions of evaluation parameters after Monte Carlo simulation on combined effects of uncertainty

4. Conclusions and discussion

The inclusion of a MBT plant into the ISWM system has been often a consequence of legislation modifications that force to treat the RUW fraction before landfill disposal. The advantages of this intermediate step on the overall system performance are due to the possibility of removal of hazardous substances or recyclable material after the collection. In particular, the separation and stabilization of the organic part reduce the contamination due to gas and leachate emissions in landfill. Moreover, the MBT plant results to be a buffer for the variations in waste composition due to changes in degree of SC.

In this work, a MBT plant for RDF production and metal recovery is modelled considering mass, energy and exergy balances. The aim is to evaluate the performance of the plant under an Exergoeconomic perspective, considering the influence of aleatory variations of external and internal operating parameters. The use of exergy in this context appeared to be particularly useful since material and non-material streams are involved. Besides, Exergoeconomics results a valuable approach for allocating the cost of the products considering the exergy invested and destroyed in each equipment and so the distribution of the irreversibility in the system.

Two different structures of MBT chain are compared, basing on real plant layouts. First of all, a sensitivity analysis is performed for evaluating the system response to a linear variation of the input variables. The degree of separation of paper, plastic and organic matter is varied in a range of ±30% with respect to the base case; in this way the resulted inlet RUW will be influenced in terms of carbon and moisture content. The more affected parameters are the Yield of RDF and the products unit exergy cost. The effect of the internal variable is tested by varying the energy consumption of the equipment between the minimum and maximum value reported in literature; the influence on output parameters results to be considerably lower.

The Exergoeconomic analysis gives practical indications for both managing and designing a new plant. The distribution of irreversibility shows that the material losses has a primary role in this kind of plant. The sequence of the equipment and the lack of efficiency that each one entails influence the final product unit costs; therefore, it has to be accurately considered in the design of the plant, which is a trade-off between the quality of RDF and recovered metals and the global exergy and economic cost. For the two analysed chains, the pre-screening phase, the NIR separator and the third hammer mill strongly influence the energy consumption and material losses, leading to a lower Yield and exergy efficiency. Since these equipment are necessary for assuring the characteristics required for the RDF (used in a cement kiln), their functioning has to be accurately monitored and optimized.

Since the real working conditions of the plant can vary stochastically, a sensitivity analysis to external (waste composition) and internal (electric equipment energy consumption) uncertain variables is conducted. A Monte Carlo simulation is adopted for sampling from uniform and normal distribution of external and internal variables, respectively. The resulted mean values and RStD of efficiencies, costs and energy consumption can be useful at the time of designing a new plant, e.g. considering the range of variation of selective collection in a certain area or the potential fluctuations in energy consumption. The analysis of the uncertainties confirms the primary importance of external variations over internal ones. In any case, the structure of the MBT plant tends to absorb and uniform the input fluctuations; this is consistent to the fact that those plants are aimed at manufacturing products with standard characteristics, or at least in certain ranges.

Future developments of the work will regard the extension of the analysis to the overall ISWM system, including the recycling treatment plants. In this case, the exergy cost of different paths can be calculated in order to optimally allocate the material streams within the system.

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