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Abstract:
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 to enhance the value of the wastes by recovering materials and energy. Anyway, MSW management is still a crucial issue, since it involves political choices other than technological and social factors. For this reason, those systems are affected by a high degree of uncertainty, which is due to external (e.g. composition of waste) and internal (e.g. energy consumption) elements. The aim of this paper is to use the Embodied Exergy criteria to evaluate the allocation of the material streams into the MSW treatment system, according to the variety of operating conditions that can be faced. Mass, energy and exergy balances have been calculated for two different treatment paths: a Mechanical Biological Treatment (MBT) plant for unsorted MSW, for Refuse Derived Fuel (RDF) production and metal recovery; a paper recycling plant for cardboard production. Two scenarios have been analysed, based on the inlet mass flow to the MBT plant and the cardboard production. Stochastic and probabilistic tools (such as Monte Carlo simulation) have been adopted for generating simulation scenarios, in order to account for the uncertainties that occurs in external and internal parameters, respectively waste composition and energy consumption of equipment.
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Keywords:
Municipal Solid Waste, Recycle, Uncertainty analysis, Exergy analysis, Embodied exergy

1. Introduction

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 to enhance the value of the wastes by recovering materials and energy. Anyway, the development of an Integrated Solid Waste Management (ISWM) systems is still a crucial issue, since it involves political choices other than technological and social factors. MSW generation and characteristics depends on several factors: period of year and the touristic activity of the area (seasonal factors), location and density of population (geographical factors), habits and wealth of people (social and economic factors) [1]. 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*). The value of global Selective Collection SC_{gl} is defined as the percentage of MSW that is separated and collected [2]. This global value is the weighted average on the mass flow of the separated material stream m_i of the degree of selective collection of the single stream SC_i (1), namely paper, plastic, organic matter, wood, metal, glass and textile. The relation between the Total Unsorted Waste (TUW) and the Residual Unsorted Waste (RUW) (the unsorted waste before and after the selective collection, respectively) and the value of SC_{gl} are expressed by (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 collected material streams are headed to the recycling plants; the outlets of these systems are manufactured products, wastes from the recycling process and rejected materials, which cannot be treated for economic or technical reasons (i.e. lack of request in the market of recycled products). The reduced ISWM system analysed in this work includes a Mechanical Biological Treatment plant for processing RUW and a paper recycle plant for cardboard production. The MBT plant is a crucial point of the ISWM system, since it undertakes a series of operations on the RUW aimed to: (i) increase the calorific value of the RUW by separating the light and dry fraction (paper, plastic, textiles, etc.) from the wet one (organic matter), in order to produce a Refused Derived Fuel (RDF), which is sent to incinerators or cement kilns; (ii) recover the ferrous and non-ferrous metal to be devolved to recycling plants; (iii) stabilize the organic part before the final disposition; (iv) reduce the volume of wastes to be disposed in landfill [3]. Besides, the MBT works as a buffer for the variation of the selective collection. Among the recycling chains, paper recycle is a one of the most well established with the highest index of recyclability (up to 80%) [4]. Besides recycled paper substitutes a material which production cost from raw material is about 50% higher in terms of energy consumption. In this work, only cardboard production is considered, since it represents the first paper product from recycle pulp of the total European production [5]. Examples of modelling and analysis of MBT and paper recycle separately are present in literature, mainly based on material and energy balance. The influence of the input waste to MBT plant and processing technologies on RDF characteristics are studied in [6]. Experimental analyses are conducted with the aim to show the environmental advantage of insert a MBT plant before landfill [7]. In [8], a Life Cycle Assessment (LCA) approach is used for evaluating the energetic and environmental performance of a MBT plant producing RDF for cement kiln co-combustion; an LCA methodology was also implemented in [3] for comparing eight European MBT plants. A comparison between virgin paper production and paper recycle using recycling metrics indicators is conducted in [9]. An assessment of pulp and paper mill through energy and exergy analysis was performed in [10]. A broader vision is adopted in [11], where different waste treatment options are analysed for various material streams using exergy criteria. Since these systems involves material and non-material streams, the concept and instruments of Exergoeconomics appears particularly useful in this context. In fact, exergy is used as a rational basis for comparing flows of different nature. In addition, exergy based performance indicators give a measure of the distribution of the irreversibility trough the equipment. Among the others, the concept of Embodied Exergy (EE) results to be an effective way for accounting the exergy invested in the entire production chain, from the extraction, processing and transport of raw materials to the process itself [12]. In real working conditions, the operation of these kind of systems is strongly influenced by social, political and economic elements, which entail a high degree of uncertainty. The uncertain factors can be: external and site-dependent, such as the structure of collection system and the degree of selective collection, which influence the waste composition; internal to the system, as the structure of each treatment chain or malfunctions in equipment, which lead to variable energy consumption. In order to reproduce these conditions in the sensitivity analysis, stochastic and probabilistic tools are adopted for generating simulation scenarios [13]. In this work, a crude Monte Carlo method was used to sample from a uniform distributions of SC_i, in order to reproduce the randomness in UW composition. The internal uncertainties are associated with the energy consumption of the equipment, since it depends from the characteristics of the inlet material (sizing, moisture content, density, mass flow) or random malfunctions. For this parameter, a normal probability distribution is supposed and the sampling is conducted on the Cumulative Distribution Function (CDF), using the inversion method. In summary, the aim of this paper is to use the Embodied Exergy criteria to evaluate the allocation of the material streams into the MSW treatment system, according to the variety of operating conditions that can be faced.

2. Methodology

2.1. Mass, energy and exergy balance

The following section reports the description of the steps for modelling and simulating the MBT and paper recycle plants, including the parameters used for the evaluation. The model was validated with data declared by real MBT plants and literature data of paper recycling based on BAT [5], by comparing the values of yield, LHV and moisture content of products and global energy consumption. All the modelling and simulation were performed in Matlab environment. The MBT chain considered in this work is composed in order by the following phases: first shredding, pre-screening, magnetic separation, eddy current separation, storage, second shredding, fine screening, Near-Infrared Removal (NIR), third shredding. The paper recycle plant was modelled considering only two macro parts: stock preparation, which includes screening, shredding an pulping; paper making process, namely pulp magnetic separation and screening, spraying, drying and pressing. The characteristics of each equipment are summarized in Table 1.

2.1.1. Mass balance

Since the relations between the inputs and outputs of the systems are 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 introduced by [14] is used (see Appendix A). 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 each equipment.

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

In order to perform the calculation, some assumptions were made on the repartition of the inlet material streams: Organic Matter (OM) stream is composed by organic waste, garden trimmings, wood, leather; 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 [15]; Other Inorganics (OI) include mostly inert and a small percentage (0.31%) of batteries and dangerous waste. Wet and dry part and ultimate analysis are calculated according to the values found in literature [16]. As evaluation parameter, the Yield of RDF is calculated as the ratio between the outlet RDF and the inlet RUW flow, $Yield(\%) = \dot{m}_{RDF}/\dot{m}_{RUW}$. For paper recycle, recovery factor and percentage of water are given on inlet paper basis. The water consumption for pulping formation varies from 1.5 to 35 m^3/ton of paper, while waste water and waste fibres are 5.4% and 1.62% respectively of the inlet paper [16, 17].

2.1.2. 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 of inlet RUW) is indicated for each equipment, Table 1 resumes the energy consumptions of the equipment included in treatment chain considered in this work. For calculating the Lower Heating Value (LHV) of the inlet material and the outlet fuel, the Mendeliev equation was adopted (4) were the coefficient of Carbon, Hydrogen, Oxygen, Sulphur (C, H, O, S) and the Moisture Content (MC) are on wet basis.

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

In case of paper recycle, electric consumption are associated to the movement of the material and pulping formation and depends on the type and quality of paper grade [17]. In this case, the deinking and dispersion phases are not considered, since cardboard is produced; this reduces considerably the global energy consumption, which is defined as the direct sum of the consumption of every equipment plus the one of auxiliaries. Thermal needs for drying purposes are usually covered by superheated steam (428 K, 1 bar [10]); in this case the steam consumption is 5.54 kg of steam/kg of paper.

Table 1- Equipment description and energy consumption, elaborated by the author based on [3,5,16,18,19]

MBT plant		
Equipment	Description	Range of Energy consumption (kWh/Mg)
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
Secondary shredding	The air-classified light fraction requires more energy for shredding than the mixed waste	15 ÷ 25
Magnetic separator	Removal of ferrous metal. The energy consumption is due to the movement system of the conveyor belt.	0.2 ÷ 2.4
Eddy current separator	Removal of non-ferrous metal.	0.7 ÷ 1.2
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
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
NIR (Near Infrared Removal)	Removal of hard plastic (PVC) trough optical separation with an infrared generator.	3.3 ÷ 6.1
Third 'Rocket' shredding	Hard shredding with hammer mill. High energy consumption and maintenance but good quality of RDF.	33.6 ÷ 62.4
Auxiliary		
Conveyor/Raising	Empirical relation for a belt length L=20m and a raising height H=2m.	6.722e-03/ 5.46e-03
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
Paper recycle		
Stock preparation	Screening and cutting of inlet paper	150-250
Paper making	Conveyor for magnetic separation, vibrant screening, spraying and pressing	150-300

Table 1-Equipment description and energy consumption, elaborated by the author based on [3,5,16,18,19,20]

2.1.3. Exergy balance

The chemical exergy content of organic materials B_{ch_i} is calculated using (5), where φ is the coefficient of correction of LHV, proposed by Szargut [21] and depending on the O/C ratio, while W ad S are the water and sulphur content (%).

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

The exergy of the mixed waste $\dot{B}_{RUW_{in}}$ (kW) was evaluated by considering the organic, inorganic and water content separately. In this case the organic part includes the streams that contains mainly carbon (C) and hydrogen (H), namely paper, organic matter, plastics, textiles. Regarding the inorganic part, the exergy of pure iron and aluminium was assumed for ferrous and non-ferrous metal respectively; the exergy of glass was 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). For the water W, only the chemical exergy was considered, since reference temperature (T_0) and pressure (p_0) were assumed. The exergy of the steam was calculated considering the contribution of physical ($b_{ph} = (h - h_0) - T_0(s - s_0)$), and chemical exergy. Second Law Efficiencies $\eta_{ex} = \dot{B}_{pr}/\dot{B}_{input}$ are evaluated for the two plants, as the ratio between the exergy of the products and the total input exergy.

2.2. The Embodied Exergy concept

Using the definition of [22], the Embodied Exergy (EE) is defined as the sum of the actual exergy of the system or product plus the exergy previously used to produce and provide the resources for creating it. As stated in [12], the EE balance is a product-specific methodology to account the consumption mode of energy embodied in the product lifecycle. Therefore, the enlargement of the boundaries of the system will lead to a more accurate evaluation of all the contribution to the EE of the products, which in this case are RDF fuel and cardboard; besides, it is useful in order to account for the avoided exergy and material consumption of the alternative scenarios. For this reason, the exergy cost of extraction (or collection, in case of MSW), process and transport of raw materials are included in the global balance, in addition to the contribution of the single treatment process. Assuming that the RDF is used in a cement kiln, the substitute fuel can be the pulverized coal [23], while the alternative process to paper recycling for cardboard production is mechanical pulping with wood as raw material. The exergy used to extract and process the coal is accounted for using the Thermo-Ecological Cost (TEC) indicator [24], supposing barge transport; the exergy cost for processing wood $Ex_{woo\ \ pr}$ includes the harvesting and transportation in a radius of 80 km [25]. The contribution of the input waste collection and transport ($Ex_{UW_{tr}}$ and $Ex_{paper_{tr}}$) are calculated considering an average distance of 30 km between the generation point and the treatment plant [26]. All these factors are calculated in terms of diesel consumption ($Ex_{diesel} = 45.6\ MJ/kg$). Table 2 resumes all the terms, internal and external to the process, used for calculating the EE balances expressed by (6-9), for RDF, paper from recycle, paper from wood and coal respectively. The balances are expressed in kW, being $\dot{B}$ the product between the specific exergy and the mass flow.

Table 2-Balance of embodied exergy for each stream; reported values are calculated by the author basing on [15, 23, 24, 25]

Waste	$Ex_{UW_{tr}}$	0.289	MJ_{ex}/kg	$EE_{RDF} = \dot{B}_{el\_MBT} + \dot{B}_{UW} - \dot{B}_{rej} + \dot{B}_{tr_{UW}}$	(6)
Paper	$Ex_{pap_{mix}}$	19.093	MJ_{ex}/kg	$EE_{card_{rec}} = \dot{B}_{el_{rec}} + \dot{B}_{paper_{mix}} + \dot{B}_{steam} + \dot{B}_{water} - \dot{B}_{fib} + \dot{B}_{tr_{pap}}$	(7)
	Ex_{fib}	18.624	MJ_{ex}/kg		
	$Ex_{paper_{tr}}$	0.235	MJ_{ex}/kg		
Wood	$Ex_{wood_{ch}}$	19.223	MJ_{ex}/kg	$EE_{card_{wood}} = \dot{B}_{el} + \dot{B}_{wood_{pr}} + \dot{B}_{wood_{ch}} + \dot{B}_{water} - \dot{B}_{fib}$	(8)
	$Ex_{wood_{pr}}$	0.51	MJ_{ex}/kg		
Coal	TEC_{coal}	1.12	MJ_{ex}/MJ	$EE_{coal} = \Delta En_{RDF} \cdot TEC_{coal} + \dot{B}_{tr_{coal}}$	(9)
	$Ex_{coal_{tr}}$	3.1	MJ_{ex}/kg		

The difference in global EE balance (10) is expressed by the algebraic sum of the difference of all the terms respect to the base case scenario (ΔEE_i); for example, an increase in SC_{paper} will lead to an increase in $EE_{card_{rec}}$ and EE_{coal} ($\Delta EE > 0$) and a decrease in EE_{RDF} and virgin paper $EE_{card_{wood}}$ ($\Delta EE < 0$).

$$\Delta EE_{gl} = \Delta EE_{RDF} + \Delta EE_{card_{rec}} + \Delta EE_{card_{wood}} + \Delta EE_{coal} \qquad (10)$$

The presented global embodied exergy balance can be considered as an opportunity cost, since it is an indicator of the savings or additional consumption encountered when a certain scenario is chosen respect to the base case (determined in terms of % SC_{paper}). Since the EE is considered as the exergy cost B_i^* of products, an unit exergy cost of the material stream c_i^* can be defined by dividing B_i^* by the corresponding exergy, $c_i^* = B_i^*/B_i$. As stated in [23], the exergy cost is an emergent property, so it acquires value only for comparing the cost of different flows in a given structure. In this case, the unit exergy based costs of RDF and cardboard are calculated.

2.3. Sensitivity analysis

First, a sensitivity analysis is performed by varying the SC_{paper} in a range between -30/+30% respect to the base case, which characteristics are summarized in Table 3. The effect of the linear variation is investigated for two simulation scenarios: (A) fixed cardboard production $\dot{m}_{card}$; (B) fixed MBT input mass flow $\dot{m}_{RUW}$ and fixed $\dot{m}_{card}$. The second case is the more realistic, since the plants are always designed for working at a Nominal Capacity (NC) or in order to reach a certain production. The idea is to account the sensitivity of the system to the variation of the input conditions and to the exergy costs that derive from it. In fact, if the generation of RUW is different from the NC of the MBT plant, an additional cost of transport is to be accounting for importing ($\dot{m}_{RUW}$ lower than NC) or exporting ($\dot{m}_{RUW}$ higher than NC) the remaining RUW from or to another waste transfer station (which is supposed to be in an area of 50 km). On the other side, a virgin paper production plant covers the fluctuations in cardboard production due to variations in paper input to recycle plant.

Table 3-Base case characteristics of waste composition (data declared for the metropolitan city of Torino, Italy [27]*)*

Material Stream	Gravimetric composition of TUW	% SC_i	Internal repartition of SC (%)
	%wg (w.b)	w.b.	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
		% SC_{gl} 51.7	

2.4. External uncertainties

The inclusion of uncertainties in waste composition is performed trough a random sampling on uniform distributions of SC_i values using a Monte Carlo simulation, which is based on the random generation of a high number of values. The ranges of SC_i have been defined after an extent review of data available in Italian scenario; at the end, 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 SC are calculated. As always, the percentage composition of the TUW before the collection is assumed to be constant. The output parameters are evaluated according to their probability distribution, considering the mean value μ and the Relative Standard Deviation (%RStD). The mean value is particularly interesting in this kind of analysis since it represents the most probable value of SC_{gl} obtained by a random variation and combination of the values of $SC_{i.}$

2.5. Internal uncertainties

The internal uncertainties are associated with the energy consumption of the equipment, which can present an aleatory behaviour. Differently from the case of external uncertainties, the equipment consumption is supposed to follow a normal probability distribution, centred in the mean values of the ranges indicated in Table 1. 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, and 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 (11-12) with a Monte Carlo simulation.

$$F(X) = P\{X < x\}, \textit{CFD of x distribution values} \quad (11)$$

$$U \in \{0,1\}, \;\; X = F^{-1}(U) \tag{12}$$

3. Results

3.1. The paper exergy path in MBT and recycle

The allocation of the paper stream in a specific treatment path entails a different destiny for its internal exergy. The distribution of exergy losses is displayed in the Grassmann diagrams (Figure 1), visualizing the contribution of material losses for the MBT plant (a) and the paper recycle chain (b). The major losses of internal (chemical) exergy of paper are associated to the equipment with the higher degrees of material losses, namely the primary and secondary screening phase, followed by the eddy current and magnetic separators. All others components contribute for a non-significant part. The portion of recovered internal exergy of paper is major in case of paper recycle (82% versus 73.2%), due to the small amount of rejected fibres.

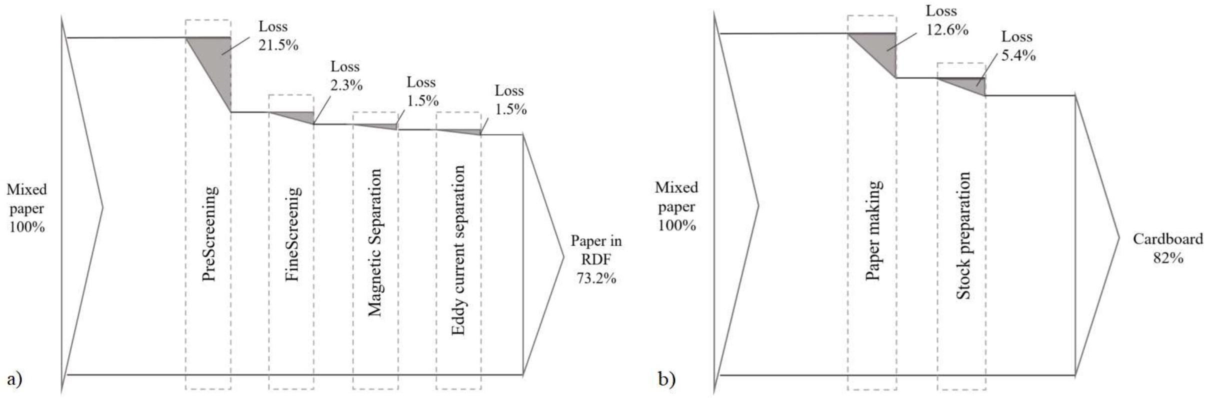

Figure 1-Grassmann diagram representing the exergy destruction due to material losses for MBT plant (a) and paper recycle (b)

3.2. Global Embodied Exergy Balance

The results of the linear variation of SC_{paper} are reported in Table 4 for the two simulation scenarios; the behaviour of each ΔEE_i in the reported ranges is linear. In order to perform the simulation, the cardboard production $\dot{m}_{card}$ was fixed to 2200 kg/h, while the input MBT flow to 5000 kg/h; these values are chosen according to the quantities in the base case scenario. Global embodied exergy value for the base case of the two scenarios are 28,354 kW and 27,974 kW respectively. The $\Delta EE_{UW_{tr}}$ associated to RUW transport is accounted separately.

Table 4-Ranges of evaluation parameters and ΔEE_i resulting by a linear variation of SC_{paper}

	Scenario A	**Scenario B**
	Range (min/max value)	
Exergy efficiency MBT (%)	58.3/50.9	57.8/50.9
Yield RDF (%)	40.9/29.1	40.9/29.1
Exergy RDF (kJ/kg)	19214/21817	19214/21817
ΔEE_{RDF} (kW)	+2842.8/-2843.4	+875.2/-1213.3
$\Delta EE_{card_{rec}}$ (kW)	-5668/+5669	-5668/+5669
$\Delta EE_{card_{wood}}$ (kW)	+6385/-6387	+6385/-6387
ΔEE_{coal} (kW)	-3080/+3450	+1270/-1972
$\Delta EE_{UW_{tr}}$ (kW)	+12.5/-12.5	+126.61/+61.63

In both cases the exergy efficiency of the MBT plant diminishes of about 13%, as a consequence of the less amount of paper in the final RDF; in fact, the Yield decrease (-28.8%) is not compensated by an equal increment in RDF specific exergy content (+13.5%). The exergy efficiency of the paper recycle plant is not influenced by the inlet composition, since the yield is fixed. Scenario A presents a quite symmetric distribution of values of ΔEE_i apart from ΔEE_{coal}, since it is based on the yield of RDF. This is the same cause of the asymmetry in ΔEE_{RDF} of scenario B; besides in this case ΔEE_{tr} is always positive, since it includes the transport cost for covering the capacity of the MBT plant. The trend of the resultant ΔEE_{gl} is shown in Figure 2. The greatest increments are associated to low degrees (-30%) of SC_{paper} for both scenarios (+1.73% for case A and +1.6% for case B); the major positive costs are associated to the production of cardboard from raw material, followed by the RDF production. The trend is generally decreasing, presenting a minimum of -0.53% for SC_{paper} = +20% (A) and of -0.13% for SC_{paper} = +10% (B). A new growth occurs for high percentage of SC_{paper}; this effect is more marked in scenario B, due to the higher additional costs of transport.

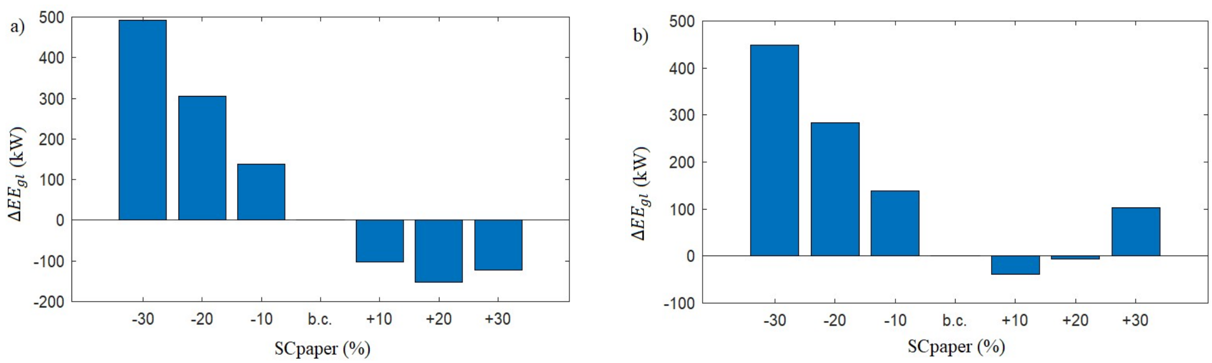

Figure 2-Difference in Global Embodied Exergy respect to the base case for the two scenarios: A) fixed $\dot{m}_{card}$; (B) fixed $\dot{m}_{RUW}$ and $\dot{m}_{card}$

3.3. The effect of uncertainties

The results of the random sampling using the Monte Carlo method and the normal sampling using the inversion method are reported in Table 5, where the values of μ and RStD are given for the main evaluation parameters. It is quite 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 SCi. The SC_{gl} values follow the behaviour of a normal probability distribution, as expected 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. Considering the external uncertainties, in a MBT plant the dispersion of values around μ diminishes for the output parameters (Yield, LHV of RDF and exergy efficiency), as demonstrated by the values of RStD. This is an effect of the transformation operated by the treatment process, which tends to homogenise the inlet material. The unit exergy cost of RDF is the less influenced by the uncertainty, showing an RStD of 1%. The trend of the evaluation parameters is graphically shown by Figure 3a. The Yield present 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. The behaviour of the EE of RDF follows the normal one, since it is influenced by the random variation of the different material streams; anyway, there is no direct correlation with one single parameter (SC_{gl}, SC_{paper}), but rather with a combination of SC_{paper} , SC_{plastic} and SC_{organic}.. Differently, the EE of cardboard present a more uniform distribution since only the paper random variation affects its behaviour; in fact, the value of the RStD is about 2.2 times higher than in the case of the EE of RDF. In the global EE balance ΔEE_{gl} is strongly influenced by the behaviour of the EE of RDF, even if the resulting distribution is not normal centred. Results show that the random variation of waste composition has a moderate effect on the global balance of EE; the major differences respect to the base case are in the range of values between -500 and +750 kW (about +/-2% of the total), which means that the various exergy cost of the system quite compensate each other.

Table 5-Mean values and standard deviations of evaluation parameters resulting by uncertainty analysis

	External uncertainties		**Internal uncertainties**	
	μ	RStD (%)	μ	RStD (%)
SC_{gl} (%)	49.5	16.3	-	-
Yield RDF (%)	39.05	13.2	-	-
RDF LHV (kJ/kg)	15415	6.14	-	-
Exergy efficiency MBT (%)	55.9	3.9	55.2	0.14
Exergy efficiency Paper recycle (%)	-	-	79.1	0.4
Embodied exergy RDF (kW)	11296	15.5	11017	0.24
Embodied exergy Cardboard (kW)	9430.5	34.5	9940.2	0.42
Unit exergy cost RDF (kW/kW)	1.062	1	1.032	0.12
Unit exergy cost Cardboard (kW/kW)	-	-	1.249	0.42
Global energy consumption MBT (kWh/Mg)	-	-	124.15	4.2
Global energy consumption Paper recycle (kWh/Mg)	-	-	424.6	7.2

With regard to the internal uncertainties, the evaluation parameters affected by the random variation of energy consumption are the exergy efficiency, the unit exergy costs of products, the global energy consumption and, as a consequence, the embodied exergy. As it can be seen in Table 5, the RStD of the product costs and the efficiency is about two orders of magnitude lower than the one of the global energy consumption. This result is a direct consequence of the less impact of energy consumption on system efficiency; besides, as in the case of external uncertainties, it shows that the effect of variation of energy consumption is reduced within the system. As expected, the discrete distribution of the values follows the behaviour of the normal distribution, as can be seen in Figure 3b.

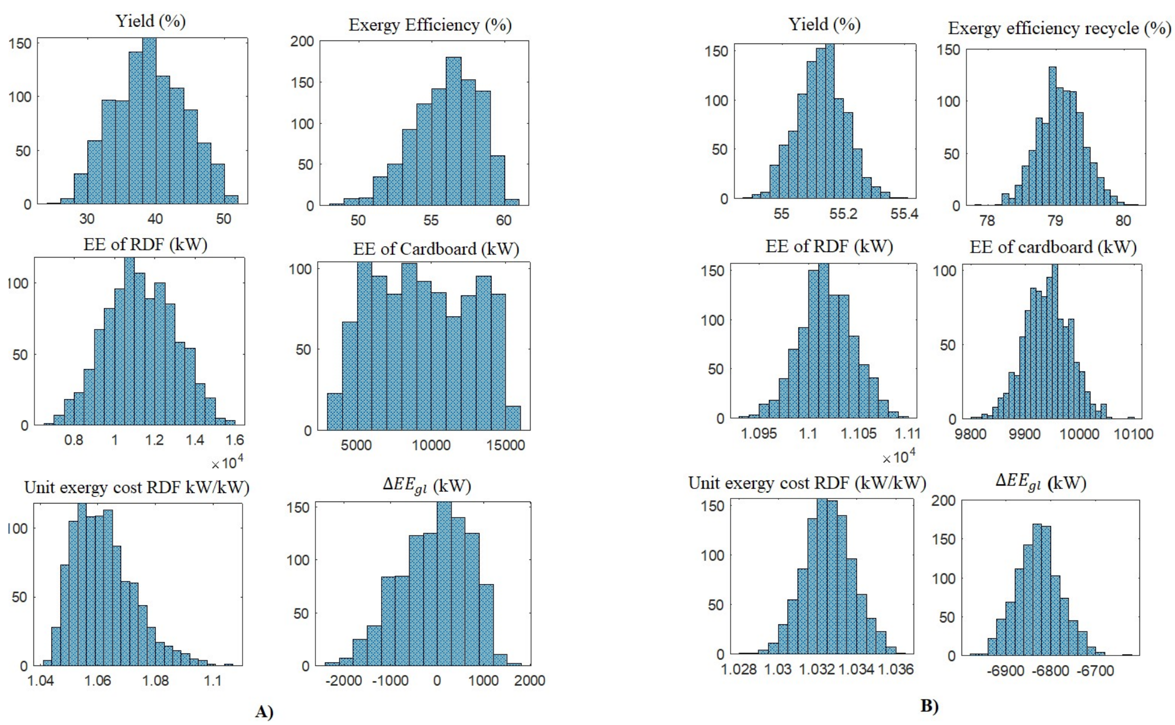

Figure 3-Distribution of values due to external (A) and internal (B) uncertainties

4. Conclusions

A Solid Waste treatment system composed by a MBT and a paper recycle plant was modelled and mass, energy and exergy balances were calculated in order to follow the path of the inlet paper material stream. In general, a paper recycle plant requires, as expected, major energy consumption with respect to a MBT plant; anyway, not only it results to be a better alternative for recovering the waste paper internal exergy, but also it is cost-effective compared with cardboard production from raw material (wood). The aim of the paper was to use the Embodied Exergy (EE) concept to evaluate the allocation of the paper material stream into the MSW treatment system, according to the variety of operating conditions that can be faced in real working conditions. The use of exergy balance in this context appeared to be particularly useful since material and non-material streams are involved. At the same time, the enlargement of the boundaries of the system had lead to a more accurate evaluation of all the contributions to the EE of the products, namely the RDF fuel and the cardboard. This idea combined with sensitivity analysis allowed the calculation of the avoided or additional exergy and material consumption of the alternative scenarios. The degree of Selective Collection of paper (SC_{paper}) was varied linearly in a range between +/-30% respect to the base case. The variation of the paper input has a moderate effect on the exergy efficiency of MBT plant, due to the combined effect on yield and LHV of RDF. It is interesting to notice the effect on the global system through the variation of the global EE: in general, a decrease in SC_{paper} leads to greater values of ΔEE_{gl}, but savings on EE diminish for high collection of paper, because of the influence of MSW transport and coal cost. Anyway, the variations are very moderate, in the order of +/- 2%. This led to the conclusion that even if the SWM system has a good degree of self-regulation, high share of selective collection can still be hindered by economic burdens, most of them linked to transport issues. An optimized location of recycling plants can reduce the global exergy cost; on the other side, RDF energy utilization should be limited to flexible systems, better if coupled with non-fossil fuels. A sensitivity analysis to external (waste composition) and internal (electric energy consumption of the equipment) uncertain variables was conducted in order to give indications for realistic working scenarios. The resulted mean values and RStD of efficiencies, costs and energy consumption can be useful at the time of designing a new plant. The analysis of the uncertainties reveals that the influence of external variations is higher than the internal ones. In any case, the structure of the system (for both the MBT and the paper recycle plant) tends to absorb and uniform the input fluctuations, even if this effect is more evident in the MBT plant. This is consistent to the fact that those plants are aimed at manufacturing products with standard characteristics, or at least in certain ranges.

Appendix A

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
Optical 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

RFTF table, elaborated by the author based on [8,14,28]

References

[1] M. E. Edjabou *et al.*, “Municipal solid waste composition: Sampling methodology, statistical analyses, and case study evaluation,” *Waste Manag.*, vol. 36, pp. 12–23, 2015.

[2] “Rapporto Rifiuti ISPRA,” 2017. http://www.isprambiente.gov.it/

[3] C. Montejo, D. Tonini, M. del C. Márquez, and T. Fruergaard Astrup, “Mechanical-biological treatment: Performance and potentials. An LCA of 8 MBT plants including waste characterization,” *J. Environ. Manage.*, vol. 128, pp. 661–673, 2013.

[4] Comieco, “Report Collection , Recycling , and Recovery of paper and board in 2017,” 2018.

[5] M. Suhr et al., *Best Available Techniques (BAT) - Reference Document on Best Available Techniques in the Pulp and Paper Industry*. 2015.

[6] N. Edo-Alcón, A. Gallardo, and F. J. Colomer-Mendoza, “Characterization of SRF from MBT plants: Influence of the input waste and of the processing technologies,” *Fuel Process. Technol.*, vol. 153, pp. 19–27, 2016.

[7] E. Trulli, N. Ferronato, V. Torretta, M. Piscitelli, S. Masi, and I. Mancini, “Sustainable mechanical biological treatment of solid waste in urbanized areas with low recycling rates,” *Waste Manag.*, vol. 71, pp. 556–564, 2018.

[8] M. Grosso, S. Dellavedova, L. Rigamonti, and S. Scotti, “Case study of an MBT plant producing SRF for cement kiln co-combustion, coupled with a bioreactor landfill for process residues,” *Waste Manag.*, vol. 47, pp. 267–275, 2016.

[9] S. Van Ewijk, J. A. Stegemann, and P. Ekins, “Global Life Cycle Paper Flows , Recycling Metrics , and Material Efficiency,” vol. 22, no. 4, 2017.

[10] Z. Utlu and O. Kincay, “An assessment of a pulp and paper mill through energy and exergy analyses,” *Energy*, vol. 57, pp. 565–573, 2013.

[11] J. P. Dewulf and H. R. Van Langenhove, “Quantitative Assessment of Solid Waste Treatment Systems in the Industrial Ecology Perspective by Exergy Analysis,” *Environ. Sci. Technol.*, vol. 36, no. 5, pp. 1130–1135, Mar. 2002.

[12] M. Liao, C. Ma, D. Yao, and H. Liu, “Decomposition of embodied exergy flows in manufactured products and implications for carbon tariff policies,” *Asia Eur. J.*, vol. 11, no. 3, pp. 265–283, 2013.
[13] J. Clavreul, D. Guyonnet, T. H. Christensen, J. Clavreul, D. Guyonnet, and T. H. Christensen, “Quantifying uncertainty in LCA-modelling of waste management systems",” 2012.
[14] L. F. Diaz, G. M. Savage, and C. G. Golueke, *Resource Recovery from Municipal Solid Wastes: Primary processing*. CRC Press, 1982.
[15] L. M. Cafiero, M. Coronidi, G. Pescheta, and N. Faustini, “Caratterizzazione e trattamento di rifiuti costituiti da assorbenti igienici,” pp. 54–64, 2010.
[16] E. Liley *et al.*, *Chemical Engineers' Handbook. Second edition (Perry, John H., ed.)*, vol. 19, no. 9. 1942.
[17] J. Laurijssen, “Energy use in the paper industry-An assessment of improvement potentials at different levels,” 2013.
[18] A. Westenbroek, “Maximum value from paper for recycling Towards a multi-product paper mill,” vol. 2011, 2011.
[19] P. Sirini, G. Tchobanoglous, and R. C. Noto La Diega, *Ingegneria dei rifiuti solidi*. Milano: McGraw-Hill, 2010.
[20] NREL, “Data Summary of Municipal Solid Waste Management Alternatives,” vol. IV, Append, no. October, 1992.
[21] S. F. Szargut J, David RM, *Exergy analysis of thermal, chemical, and metallurgical processes. Hemisphere Publishing, New York*. New York: Hemisphere Publishing, 1988.
[22] S. Ulgiati, “Energy, Emergy and Embodied Exergy: deverging or converging approaches?,” *First Bienn. Emergy Anal. Res. Conf.*, pp. 15–31, 2000.
[23] S. R. Asthana and R. K. Pati, “Use of Alternative Fuels in Indian Cement Industry,” *Adv. Energy Res.*, no. July, pp. 347–349, 2006.
[24] W. Stanek, Ed., *Thermodynamics for sustainable management of natural resources*. Springer, 2017.
[25] M. A. Furtula, G. J. Danon, V. V. Bajić, and D. N. Lukačev, “Energy consumption and equivalent emission of Co2tpellet at wood pellets production in Serbia,” *Therm. Sci.*, vol. 21, no. 5, pp. 1905–1915, 2017.
[26] Larsen, Anna & Vrgoc, Marko & Christensen, Thomas & Lieberknecht, Poul. (2009)." Diesel consumption in waste collection and transport and its environmental significance". Waste management & research : the journal of the International Solid Wastes and Public Cleansing Association, ISWA. 27. 652-9.
[27] ATO RIFIUTI, “RIFIUTI URBANI : PRODUZIONE E RACCOLTA DIFFERENZIATA,” pp. 17–64, 2015., http://www.atorifiutitorinese.it/cms/