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# Influencing factors of Solid Waste Management global cost and efficiency: a multi-objective optimization focusing on the collection system

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**Abstract.** Development of an Integrated Solid Waste Management (ISWM) system is a continuous challenge for local communities. These systems should be properly designed, paying particular attention to the optimal connection of their subsystems. Among them, the Solid Waste (SW) collection system has a primary influence. The design variables (e.g. unit collection basin and weekly removal) can be optimized according to the variation of external parameters (e.g. penetration of selective collection, population density). The objective is the minimization of specific collection cost, maintaining the maximum collection efficiency. Once the collection system is optimized, its influence on the entire SW treatment chain is evaluated. To this end, a multi-objective optimization is implemented taking into account the global cost and exergy efficiency of waste treatment. The analysed system is composed by a paper recycling plant for cardboard production and a Mechanical Biological Treatment plant for the Residual Unsorted Waste treatment, with production of Refused Derived Fuel.

## 1 Introduction

Solid Waste (SW) generation has seen a considerable growth in the last decades, due to the ever-increasing population and consumerism-based economy and lifestyle. At European level, many Directives have been enacted in order to assess an EU Waste legislation. Most of them set the standards for the treatment of the single materials streams or commodities (e.g. packaging, electronic waste, vehicles, organic waste) [1]. The Directive 2008/98/EC establishes a legal framework for waste treatment in the EU Member States. However, practical design, planning and policy implementation are handled by the single countries, since the correct combination of waste management activities is strictly linked to the characteristics of local communities. An Integrated Solid Waste Management (ISWM) system (ISWM) is defined as "the comprehensive waste prevention, recycling, composting, and disposal program" [2]. The goal of an efficient ISWM is to optimize the operation and connection between its subsystems according to environmental and human health safety

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principles and including the economic constraints. Among all the constituting parts of an ISWM, the SW Collection and Transport (C&T) system surely has a crucial role. It represents the first economic burden associated to the waste after generation. Besides, it has strong influence on SW treatment plant location and operation. For these reasons, a deep understating of SW C&T influencing factors is essential. The analysis of waste C&T is widely diffused in literature, even with different approach and goals. Many works deal with the vehicle routing optimization [3][4], or plant location-allocation based on GIS systems [5][6]. Other studies are focused on the understanding of the relations between the influencing factors through mathematical models and real data collection. In [7], the impact of SW source segregation on the fuel consumption and collection cost is evaluated. In [8][9], different methods are developed for analysing the drivers of the SW collection cost and efficiency, basing on Italian data. Techno-economic performance indicators of SW collection strategies are developed in [10]. The present work falls into the second category of studies, since it shows the correlation of various factors (e.g. population density, unit collection basin, degree of Selective Collection, *SC*) and their influence on the collection cost, considering a typical Italian C&T system. The goal is also to obtain a set of optimal combination to use for the optimization of the entire SWM system. In fact, after the collection system, the other important ISWM subsystems to consider are the SW treatment and final disposal plants. They generally include: material separation facilities and recycling plants for separated material streams; Mechanical Biological Treatment (MBT) plants for Residual Unsorted Wastes (RUW) treatment; Waste-to-Energy (WtE) plants; landfills. Due to the complexity of the system, a deep focus on specific plants can be useful for understanding their functioning and the relation between them. In the present work, a reduced system including a MBT plant and a paper recycling plant for cardboard production is analysed. According to the Italian law LD 211/2015 art. 48, RUW have to be treated before being incinerated or disposed in landfill. The MBT chain separates the light and dry fraction of the RUW from the organic and wet one, increasing the calorific value of the main outlet stream, the Refused Derived Fuel (RDF) [11]. Besides, ferrous and non-ferrous metals are recovered and devolved to dedicated recycling plants. The RDF is used in WtE plants, cement kilns or it is disposed in landfill [12]; its production is a sort of buffer for the variation of *SC*. Among the recycling chains, paper recycling is one with the highest index of recyclability (up to 90%) [13]. In this work, cardboard production is considered, since it represents the main recycled pulp product in Europe; moreover, the cardboard production cost from wood cellulose is about 50% more energy intensive [14]. Different methodologies have been adopted for the analysis of the SWM [15][16] (e.g. Material Flow Analysis, Life Cycle Assessment, optimization models). Between all the techniques, the exergy-based approach appears to be a promising instrument for the analysis of the systems involving material and non-material streams, since exergy can be used as a rational basis for comparing flows of different nature. For example, an assessment of pulp and paper mill through energy and exergy analysis is performed in [17]. A broader vision is adopted in [18], where different waste treatment options are analysed for various material streams using exergy criteria. Besides, an application of Exergonomics to the analysis of a MBT plant has been already proposed by the authors in [19]. The Embodied Exergy (EE) concept (i.e. the amount of exergy invested in the entire production chain, from the extraction, processing and transport of raw materials to the manufacturing process itself [20]) results effective in evaluating the global resource footprint of a process or product. The EE approach acquires even more interest when alternative scenarios for the production or supply of the same commodity are included in the analysis. Even in SWM, especially when the final treatment involves recycled products manufacturing, it appears fundamental to include the minimization of the resource consumption in the decision making process, together with the minimization of the monetary cost. A Multi-Objective Functions (MOFs) optimization [21] results to be the appropriate choice for this type of systems. In the second

part of the work a multi-objective optimization is implemented taking into account the global cost and EE efficiency of a reduced SW treatment system according to the degree of selective collection.

## 2 Modelling and methodology

### 2.1 The SW collection system

Regarding the SW C&T, there are two main collection schemes: i) kerbside (or 'door-to-door') collection, when the waste is daily collected from every housing unit, according to the type of material; ii) traditional (or 'bring point') collection, when the waste is dropped off in separated street bins. In Italy, the recent trend is to gradually change in favour of the kerbside collection, since it allows to reach higher degree of selective collection, with moderate cost increment. According to [22], citizens that practice kerbside separation have a higher recycling conscience and are more satisfied with the city waste management system. In this work, a typical Italian kerbside collection system is modelled. Small rear-loader trucks handle the door-to-door collection; when they reach their collection capacity $V_{st}$, the waste is unloaded into bigger trucks (with $V_{bt}$ capacity) and transported to the transfer stations where it is displaced to the various treatment plants. The first action in order to plan the SW collection scheme consists in the estimation of the number of small and big trucks, $N_{st}$ and $N_{bt}$. It depends from various factors, as follows.

o *Route time.* The time of an entire route $t_{st}$ (Eq. 1) for the small rear-loader truck is calculated as the sum of the collection time $t_{coll}$ (Eq. 2), which depends on the picking time $t_p$ and the waste volume $V_p$ at the collection point, and the dropping off time into the big truck $t_{drop}$. A recovery time factor $W$ takes into account the distance between the collection points and it is strongly linked to the population density. The maximum number of rounds in a working day of $H_{day} = 8$ hours is $N_d = H_{day}/t_{st}$.

$$t_{st} = \frac{t_{drop} + t_{coll}}{1 - W} \tag{1}$$

$$t_{coll} = \frac{t_p \cdot V_{st}}{Vp} \tag{2}$$

o *Weekly SW generation.* The collection routing is planned on a weekly basis, setting a number of weekly removal $N_w$. To this end, the generated volume of i-th waste stream $V_{w_i}$ is calculated as in Eq.3 by the product of the pro-capita generation $V_{pc_i}$ and the unit collection basin $U_b$, which is the reference district used for designing the collection scheme.

$$V_{w_i} = V_{pc_i} \cdot U_b \tag{3}$$

Considering these factors, the number of small trucks necessary for the collection in $U_b$ is given by Eq. 4. The number of small trucks serving the entire urban centre $N_{st}^{tot}$ is calculated in Eq. 5, considering the total population $P_{tot}$ and the fact that the same trucks can be used in different days ($D_w = 7$) and districts during the week, depending on their availability. From author considerations and literature review, the number of big trucks $N_{bt}$ is estimated to be the half of the small ones $N_{st}$.

$$N_{st}^{U_b} = sup\left(\frac{V_{w_i}}{V_{st} \cdot N_w \cdot N_d}\right) \qquad (4)$$

$$N_{st}^{tot} = sup\left(N_{st}^{U_b} \cdot \frac{P_{tot} \cdot N_w}{U_b \cdot D_w}\right) \qquad (5)$$

The trucks estimation allows the calculation of the specific costs, namely: the fixed cost associated to the vehicles purchase and maintenance; the operation cost associated to fuel consumption; the labour cost.

o  *Purchase cost.* The annual depreciation of the j-th vehicle $C_{a_j}$ (Eq. 6) is calculated given the purchase cost $C_{fix_j}$ and the percentage of insurance (*Ins*) maintenance (*Maint*) and taxation (*Tax*) on the annual cost. The actualization factor $f_{a_j}$ (Eq. 7) depends on the interest rate $i_j$ and the annual recovery period $Y_{rec_j}$. Equation 8 gives the specific cost per unit volume of waste due to the purchasing.

$$C_{a_j} = (1 + Ins_j + Maint_j + Tax_j) \cdot f_{a_j} \cdot C_{fix_j} \qquad (6)$$

$$f_{a_j} = \frac{i_j \cdot (1 + i_j)^{Y_{rec_j}}}{(1 + i_j)^{Y_{rec_j}} - 1} \qquad (7)$$

$$c_{v_{fix}} = \frac{N_{st}^{tot} \cdot C_{a_{st}} + N_{bt}^{tot} \cdot C_{a_{bt}}}{V_{w_i} \cdot week_{year}} \qquad (8)$$

o  *Fuel cost.* The cost associated to fuel consumption depends on the vehicle hourly productivity $P_{h_j}$ (Eq. 9), which accounts for the equivalent kilometres $K_j$ travelled by the vehicle during a working day. For small trucks $K_{st} = t_{st} \cdot \bar{v}_{st}$, where $\bar{v}_{st}$ is their average velocity, namely 30 km/h, while for big trucks $K_{bt} = 2 \times d_{ts}$, where $d_{ts}$ is the distance between the last drop point and the transfer station. The specific cost per unit volume of waste due to the fuel consumption is given by Eq. 10, which includes the fuel cost and the specific fuel consumption.

$$P_{h_j} = \frac{N_d \cdot K_j \cdot N_j^{tot}}{H_{day}} \qquad (9)$$

$$c_{v_{fuel}} = \sum_j \frac{c_{fuel} \cdot P_{h_j} \cdot H_{day} \cdot N_w}{cons_{fuel_j} \cdot V_{w_i}} \ , \ j \in \{st, bt\} \qquad (10)$$

o  *Labour cost.* Equation 11 gives the cost per unit volume of waste due to the personnel cost, in the hypothesis of one employee for each vehicle. The average salary *Sal* is chosen according to Italian survey.

$$c_{v_{lab}} = \frac{(N_{st}^{tot} + N_{bt}^{tot}) \cdot Sal}{H_{day} \cdot D_w \cdot week_{year}} \qquad (11)$$

The total specific cost per unit of volume of the i-th waste stream is the sum of the three contribution, namely $c_v^{tot} = c_{v_{fix}} + c_{v_{fuel}} + c_{v_{lab}}$. The specific cost per unit of mass is then calculated considering a RUW density $\rho_{RUW} = 80$ kg/m³. When planning the collection scheme, removal efficiency is supposed to be the maximum achievable. To this end, data on recent years pro-capita generation are gathered [23] and degree of primary source segregation (i.e. material separation by the end-users) are supposed. In order to understand the relation

between the influencing factors on the specific cost, sensitivity of the system is tested according to the variation of key parameters, namely: the population density $W$, the number of weekly removal $N_w$, the unit collection basin $U_b$ and the total population $P_{tot}$. Among them, $N_w$ and $U_b$ are project variables, since they can be decided during the design phase, while $W$ and $P_{tot}$ are linked to the local context. All the other fixed parameters are specified in Table 1.

**Table 1**. Parameters used in the SW collection model, based on [24] and Italian municipalities reports on SW collection

| $t_{drop}$ [hours] | 0.1 | | $V_{st}$ [m$^3$] | 10 | |
|---|---|---|---|---|---|
| $t_p$ [hours/point] | 0.015 | | $H_{day}$ [hours/day] | 8 | |
| $V_p$ [m$^3$/point] | 0.2 | | $d_{ts}$ [km] | 25 | |
| $V_{pc_{RUW}}$ [kg/day] | 1.3 | | $week_{year}$ | 48 | |
| $c_{fuel}$ [€/L] | 1.55 | | $Sal$ [€/year] | 40,913 | |
| | *st* | *bt* | | *st* | *bt* |
| $Y_{rec}$ [year] | 5 | 7 | $Ins$ [%] | 0.72 | 1.7 |
| $cons_{fuel}$ [l/km] | 7 | 2 | $Tax$ [%] | 1.03 | 0.4 |
| $C_{fix}$ [€] | 50,000 | 145,000 | $Maint$ [%] | 8.9 | 9.3 |

*st*: small truck; *bt*: big truck.

## 2.2 The SW treatment system

The reduced SW treatment system composed by a MBT plant and a paper recycling plant is modelled. The structure of the MBT chain consists, in order, of first shredding, pre-screening, magnetic separation, eddy current separation, storage, second shredding, fine screening, Near-Infrared Removal (NIR) and third shredding. The aim is to produce the Refused Derived Fuel (RDF) to be used in WtE plants or cement kilns. The operation of the plant has been deeply analysed in [19], which is the reference for the Recovery Factor Transfer Function (RFTF) matrix used for mass balance, the energy consumption and cost of each equipment and the calculation of the material streams exergy content. The paper recycling plant includes the stock preparation (i.e. screening, shredding and pulping of the inlet paper material) and the cardboard making process (i.e. pulp magnetic screening, spraying, drying and pressing). The equipment characteristics and energy consumption, as well as the paper recovery factor, steam and water consumption, waste in paper stream and rejected fibres are selected according to [14][25] and are reported in Tab. 2. Detailed characterization of the processes allows the calculation of the EE balance, which is a product-specific methodology to account the consumption mode of energy embodied in the product lifecycle [20]. The end-chain products that exit the system boundaries are the RDF and the recycled cardboard. The resource invested in collection and transport of raw material (i.e. SW) are accounted in the global balance, as well as the contribution of the single treatment process (i.e. MBT or recycling). In the hypothesis that the RDF is burnt in a cement kiln, the general substitute fuel is pulverized coal [26], while the alternative process to cardboard production is mechanical pulping with wood as raw material. The Thermo-Ecological Cost (TEC) indicator [27] is used to account the exergy used to extract and process the coal. The exergy cost for processing and transporting wood is evaluated as in [28], in terms of diesel consumption.

### 2.2.1 Multi-objective optimization

The aim of the MOFs optimization is to find the non-dominated solution set, which is called the Pareto-optimal set (or front). In practice, the Pareto front represents the set of solutions that define the best trade-off between the competing objectives. Various techniques have been used for moving along the Pareto curve, e.g. the weighted sum method, the ε-

constraint method, the weighted metric method. In this work, since the interest is the evaluation of all the possible trade-off solutions, the entire Pareto curve is obtained using an elitist Genetic Algorithm (GA) technique [21]. Optimization is performed in MATLAB environment. In the optimization problem (Eq. 12), the variable '*x*' is the degree of *SC* of paper, which can theoretically vary between 0 and 100. The variation in *SC* of paper have a great influence on the total *SC*, since paper stream share in total SW generation weight is consistent. The aim is to find the existing optimal configuration and their associated values of cost and efficiency. The MOFs are described as follows. All data used for the calculation are reported in Table 2.

$$\min_x C_{tot} \quad \& \quad \max_x Eff_{ex} \tag{12}$$

**Table 2** Data used for the objective functions calculation, based on [14][27][28]

| Recycling | | Exergy | |
|---|---|---|---|
| Paper recovery factor | 0.88 | Exergy of diesel [kJ/l] | 35,654 |
| SW in paper [%] | 9 | Exergy additives [kJ/kg$_{pap}$ ] | 551 |
| Waste fibres [%] | 1.62 | Exergy of NG [kJ/m$^3$] | 42,182 |
| NG consumption [m$^3$/kg$_{pap}$] | 0.087 | Exergy of wood [kJ/kg] | 19,223 |
| Electricity consumption [kJ/kg$_{card}$] | 846 | Exergy of sludge [kJ/kg] | 18,624 |
| Water consumption [kg$_{wat}$/kg$_{pap}$] | 14 | Exergy of wood trasnsport [kJ/kg] | 306 |
| **Virgin production** | | Exergy of wood harvesting [kJ/kg] | 198 |
| Electricity consumption [kJ/kg$_{pulp}$] | 3600 | TEC coal [kJ$_{ex}$/kJ$_{en}$] | 1.12 |
| Water consumption [kg$_{wat}$/kg$_{pap}$] | 20 | Exergy transport coal [kJ/kg$_{coal}$] | 2901 |
| Waste fibres [%] | 4.2 | | |
| **Costs** | | | |
| NG cost [€/m$^3$] | 0.29 | Residual disposal cost [€/kg] | 0.105 |
| Waste paper cost [€/kg] | 0.035 | Water cost [€/m$^3$] | 0.71 |
| Cardboard cost [€/kg] | 0.415 | Cellulose cost [€/kg] | 0.47 |
| Electricity cost [€/kWh] | 0.039 | Additive cost [% on cardboard production] | 1 |

o  Minimization of total cost $C_{tot}$ for the production of RDF and cardboard (Eq. 13) which is the sum of the fixed maintenance costs associated to the j-th plant $C_{maint}$, the process costs $C_{proc}$, the cost for residuals disposal $C_{rej}$, and the collection and transport cost $C_{coll}$ and $C_{tr}$ of the i-th material steams to the j-th treatment plants. For the MBT plant, $C_{maint_{MBT}}$ is calculated as the 10% of the total investment cost. The correlation (Eq. 14) is obtained from equipment cost data referring to a range of capacity *K* between 60 and 300 tons/day. $C_{proc_{MBT}}$ is linked to the electricity consumption only. With regard to the paper recycling plant, $C_{maint_{rec}}$ is about 5% of the global revenues based on cardboard production. In the process cost, the purchase of electricity, water, Natural Gas (NG) for auxiliary boiler and additives is included. For both plants, the rejects cost is the one of disposal in landfill. The cost of transport is calculated with the specific costs calculated in Eqs. 8-10-11.

$$C_{tot} = \sum_i \sum_j (C_{maint_j} + C_{proc_j} + C_{rej_j} + C_{tr_{ij}} + C_{coll_i}) \tag{13}$$

$$C_{maint_{MBT}}(K) = 289.7 \cdot \ln K - 2964.3 \tag{14}$$

o  Maximization of EE efficiency (Eq. 15), which compares the exergy of products $Ex_{RDF}$ and $Ex_{card}$ with all the exergy invested for producing them, namely the exergy of the i-th inlet material $Ex_{in}$, the exergy of the j-th process $Ex_{proc}$ and the exergy linked to the transport $Ex_{tr}$ and collection $E_{coll}$. The avoided and additional exergy cost of the alternative scenarios, i.e. virgin cardboard production $EE_{card_{vir}}$ and alternative fuel $EE_{coal}$, are included.

$$Eff_{ex} = \frac{Ex_{RDF} + Ex_{card}}{\sum_i \sum_j (Ex_{in_i} + Ex_{proc_j} + Ex_{tr_{ij}} + Ex_{coll_i}) - EE_{card_{vir}} + EE_{coal}} \qquad (15)$$

## 3. Results and discussion

### 3.1 Influencing factors on collection cost

#### 3.1.1 Sensitivity analysis

First of all, a sensitivity analysis is performed to test the influence of external factors (i.e. $P_{tot}$, $N_w$, $W$, $U_b$ and $SC$) on the collection system. As a general consideration, the total specific cost decreases with an increment in the number of inhabitants ($P_{tot}$ and $U_b$), until reaching a constant value. In practice, there are step fluctuations around a mean constant value due to the influence of an integer number of vehicles.



**Fig. 1.** Influence of various parameters on RUW specific collection cost: a) total population; b) number of weekly removal; c) population density; d) degree of selective collection.

A description of the main results is reported as follows; the inhabitants of $U_b$ are varied between 1000 and 8000 and the influence of the other parameters is tested one at a time.

- *Total population $P_{tot}$* (Fig.1a). For a given $N_w$ and $W$, the specific cost decreases with an increment in the total population. The trend of $c_m^{tot}$ with $U_b$ tends to become the same as $P_{tot}$ increases (this effect is more evident for $P_{tot}$ higher than 100,000 inhabitants); it means that the optimal collection units are almost independent from the total population of the area.
- *Number of weekly removal $N_w$* (Fig. 1b). An intensification in the waste removal frequency leads to an increment in the specific cost. In fact, the growth in the operation costs (fuel and personnel) is not compensated by the decrement associated with the reduced number of vehicles. The increment is more evident for small $U_b$, while the values tend to become more similar for high $U_b$.
- *Population density $W$* (Fig. 1c). Lower population density (associated with higher values of W) implies longer collection times, which means more vehicles for a given waste generation. Therefore, the specific cost increases with $W$. It can be noticed that the optimal combinations (i.e. values of $U_b$ for which the cost is minimum with a given $W$) increase with $W$.
- *Degree of selective collection $SC$* (Fig. 1d). In general, an increment in $SC$ leads to higher and more fluctuating costs for the RUW fraction. The cost increment with $SC$ is more marked for small $U_b$ (cost difference decrease from about 30% to 3%).

### 3.1.2. Optimal parameters

Results of the sensitivity analysis show a deep interconnection between all the parameters influencing the total specific cost. The operation variables that can be actually chosen during the design phase are $N_w$ and $U_b$. Results of optimal parameters clustering derived from a minimization of collection cost are shown in Table 3.

**Table 3** a) legend of scenarios according to total population and population density; b) clustering of optimal solutions according to SC$_{pap}$ and U$_b$

| a) | $P_{tot_1} = 30{,}000$ | $P_{tot_2} = 100{,}000$ | $P_{tot_3} = 500{,}000$ |
|---|---|---|---|
| $W_1 = 0.1$ | ● | ● | ● |
| $W_2 = 0.4$ | ● | ● | ● |
| $W_3 = 0.8$ | ● | ● | ● |

| b) | 1000-2000 | 2000-3000 | 3000-4000 | 4000-5000 | 5000-6000 | 6000-7000 | 7000-8000 |
|---|---|---|---|---|---|---|---|
| $SC_{pap} = 30\%$ | ●●● ●●● | ●● | ●● | ●● | ● | | ●● |
| $SC_{pap} = 60\%$ | ●●● | ●●● ●●● | ● | ●●● | ●● | | |
| $SC_{pap} = 90\%$ | ● | ●●● ●●● | ●●● | ●●● | ●● | | ● |

The optimization is repeated for 3 values of $P_{tot}$, $W$ and $SC$; results are clustered for ranges

of $U_b$ population. All the values are obtained in the hypothesis of a collection efficiency of 100%. Since RUW stream generally has the highest share in weight, its cost minimization results to be the best choice for design purposes. All the optimal solutions result to correspond to only one weekly removal, $N_w$=1, which is coherent with the outcomes of the sensitivity analysis. The cluster shows that the majority (83%) of optimal solutions are associated to $U_b < 5000$ inhabitants. The fact that one configuration appears in more clusters is because more than one solution is present for the same value of minimum $c_m^{tot}$. This effect comes from the fluctuating trend of the cost, as already shown in Fig. 1.

### 3.2 MOFs optimization of SW treatment system

The optimal values found in the first section are used in the SW treatment model for performing the MOFs optimization. Fig. 2 shows the Pareto front deriving from the minimization of $C_{tot}$ and the maximization of $Eff_{ex}$, according to the SC of paper. In this case, the optimization is performed for $P_{tot}$=500,000 inhabitants, W=0.4 and $U_b$=2,000 and $N_w$=1. The Pareto front is not continuous and this is a consequence of the presence of integer variables into the objective functions. The ranges of EE efficiency in the optimal configurations comes from 85% to 90%, with $C_{tot}$ from 35.2 to 37.2 k€/day, and from 90% to 92.5%, but with higher costs from 41.3 to 42.2 k€/day. The values of SC associated to the optimal solutions range from 75% to 99%.
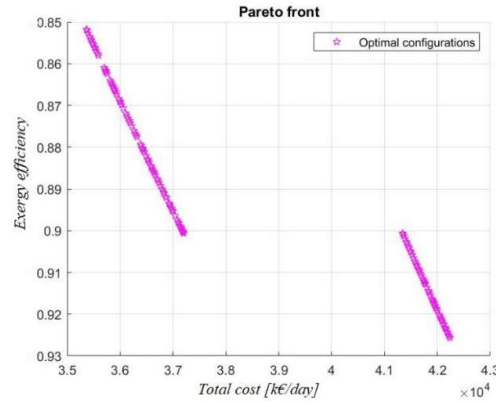


Figure 2 – Pareto front of MOFs optimization

## 3    Conclusion and discussion

In this work an analysis and optimization of Solid Waste management influencing factors is proposed, with a focus on the collection system. First, a SW collection model is proposed, based on typical scheme and data of Italian scenario. The sensitivity analysis shows that the combination of external parameters (W, SC and $P_{tot}$) and design variables ($N_w$ and $U_b$) has a strong influence on the specific collection cost $c_m^{tot}$. Minimization of the RUW $c_m^{tot}$ shows a set of possible configurations where the weekly removal is always one a week ($N_w$=1), but the range of $U_b$ alternative is wider. Therefore, it is strongly recommended to take into consideration all these factors when designing the collection scheme, choosing an appropriate collection unit basin according to all the characteristics of the area. It is also important to eventually redesign $U_b$, if significant changes in SC occur. Results obtained from the first analysis are used in a SW treatment model, including a MBT plant for RUW and a paper recycling plant. The concept of Embodied Exergy is applied to evaluate the exergy efficiency of the system, accounting not only the resources invested in the production process and collection and transport of raw materials, but also the avoided or additional exergy burdens of alternative scenarios (i.e. production of cardboard from virgin wood and purchase of coal

as alternative fuel to RDF). A MOFs optimization is performed on a particular scenario. The aim is to find the trade-off configurations, which minimize the total cost of collection and treatment and maximize the exergy efficiency of the system (including the EE of alternative scenarios); the optimization variable is the degree of *SC* of paper. Results show that many combinations are possible, all linked to high share of *SC*. An important consideration comes from the gradient of the Pareto curve: a relative small increment in cost leads to considerable increment in resource utilization efficiency. Therefore, the importance of enlarging the system boundaries of the analysis and performing MOFs optimization is confirmed.

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