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Can the New Waste Morphology Method Predict Sorting Plants Operational and Financial Challenges? A Case Study in Sharjah

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This article presents a new approach to analysing municipal waste (MSW) composition, which makes it possible to envisage sorting process efficiency and predict valuable secondary raw material (SRM) losses during sorting. The study also enables to foresee financial losses related to the quality recyclables that are reclaimed from MSW. In this article, samples from MSW delivered to Bee'ah site in Sharjah in the United Arab Emirates (UAE) were analysed to define their composition. The novelty in this research was the mechanical and physical property analysis for the MSW components and the prediction mechanism used to foresee the possible recovery rate of a potential mechanical sorting process. The results were compared with those that would be obtained from traditional composition analysis to end up with shocking results. It was concluded that any mechanical sorting process, designed based on traditional analysis data, is mostly to face tremendous operational and financial challenges in the UAE. This is due to the input material shape, size, moisture content and other factors that change the way SRM components respond to sorting mechanisms. The study was able not only to explain the challenges faced by all the UAE sorting facilities, but also to show how to prevent such unsatisfactory performance in the future. The study concluded the reasons behind the MSW component deterioration and provided additional recommendations to extract more benefits from the new waste morphology approach.

Keywords: waste, morphology, recovery, sorting, avoidance, recycling.

Introduction

The period from 2000 to 2019 witnessed revolutionary changes in the municipal solid waste (MSW) management in the European Union (EU). Stringent legislative and financial decisions were taken to turn around the situation where the rates of waste generation and disposal used to rise continuously. The EU directive 1999/31/EC on landfill of waste emphasized the importance of the principles of "polluter pays'', the directive 2008/98/EC on waste has set the rules to prevent waste generation and push towards recovery and recycling, and finally, the directive 94/62/EC, amended last time in May 2018, obliged the EU to achieve recycling rate by weight of all packaging waste of 65% by the end of 2025 and a minimum of 70% by the end of 2030. These decisions were consolidated to achieve 3 main targets (The European Parliament and the European Council, 2004):

a Minimizing MSW generation without being an impairment to the economic growth, which has become possible with the introduction of the "circular economy" concept, emphasizing and promoting the re-use of goods and products, as well as their economical processing, allowing them to be reused without significant investment (Allen Macarthur Foundation, 2013).

b Recovering maximum material from waste to be recycled and reused for same or other purposes. The EU managed to develop the secondary raw material (SRM) market by improving the quality of the collected and recovered recyclables. On the other hand, significant financial charges were imposed on manufacturers of those goods, after the use of which waste is generated and sent for disposal, by putting in practice the principle of "polluter pays" (The European Parliament and the European Council, 2004).

c Avoiding MSW disposal and incineration by implementing strict financial and procedural regulations. The introduction of such financial instrument in countries like Sweden has forced the waste-management system that works rationally from an economic perspective to apply alternative methods for waste treatment when the net costs for these are lower to ensure the competitiveness of further MSW treatment (Sahlin et al., 2007). The growth in taxation on incineration proved to have a strong negative effect on the growth of industrial plastic waste generation (Cimpan et al., 2015).

Role of recovery in MSW minimization and avoidance

Being equally vital to minimise waste disposal, the recovery stage has proven to be the most effective in diverting MSW away from landfills. In 2018, recovery processes helped to divert 79% of the MSW that was generated in the EU and created the base to boost the SRM market. By the end of 2016, the EU managed to recycle an impressive 67% of its packaging waste mainly after implementing waste source separation programmes that significantly improved the SRM quality and value. The SRM market in Europe reached its climax by achieving an SRM trade value of about 14 billion Euro in 2018 (Eurostat, 2020).

Collection as part of recovery and avoidance

Recovery efficiency is dependent, inter alia, on the waste collection method (WRAP, 2006). The different MSW collection concepts used around the world can be placed in three main categories:

a Single stream (or fully co-mingled) whereby all dry recyclables, i.e., paper (newspapers, magazines, office paper, etc.), cardboard, plastic bottles and containers, aluminium and steel beverage cans, glass and liquid carton containers are co-mingled and collected in a single compartment of a waste transportation vehicle (Damgacioglu et al., 2019).

b Two-stream (or dual-stream co-mingled), whereby recyclable materials are kept in two separate categories during collection and transportation: (1) fibre (paper and cardboard); and (2) containers (plastic, metal, and glass). In this collection method, vehicles may have two compartments to keep the materials separate (Cimpan et al., 2015).

c Mixed collection, whereby no separation is done of any sort, oversized items and food waste are mixed with other MSW components in the same compartment during transportation. This method is widely implemented for MSW collection in all Middle East region, majority of Asian and some east European countries. The MSW collected using this method is referred to in European countries as residual municipal solid waste (Rada et al., 2009). The main advantage of this system is the collection cost reduction and the convenience for the transporter. The main disadvantages are the high moisture content and organic contamination and the complexity of any sorting or recovery technology to sort the components in the waste.

Sorting as the main recovery technology

Material recovery facilities (MRF) are designed to separate co-mingled materials into their individual SRM and prepare them for sale. The MSW separation process may be carried out manually or automatically using appropriate means of identification. The more accurate and efficient the means of identification, sorting and separation, the more SRM is reclaimed and the better the quality of the recovered SRM (ISO, 2008). The engineering of MRF is greatly assisted by process modelling, which requires three types of input data (Jansen et al., 2015):

a the expected morphology of the input MSW;

b a clear description of the type of SRM that needs to be produced, and the quality specifications for that need to be attained;

c the most recent technical parameters of contemporary sorting equipment that are available in the market and their efficiency.

MSW morphology analysis methods

Knowing the expected MSW composition is the most important step to start designing the sorting process and creating the business plan based on the expected SRM quantity and its value. There is no single standard method of analysing MSW composition; however, common regionally and internationally recognized methodologies are followed in this field and referred to as composition or morphology analysis (MA) methods. The various MA methods have minor differences that can be found in surveying, sampling, presentation approaches and the pursued level of details. There are no systemized criteria for rating the existing MA methods, and it is the customer's decision to choose which one to use unless otherwise stated by authorities. Examples for country-oriented MA can be MODECOM (France), ARGUS (Germany), IBGE (Belgium) (Wavrer, 2015), and ROMECOM (Romania) (Ciuta et al., 2015). Regional and international MA methods include Solid Waste Association (SWA) tool; D 5231 – 92 Standard Test Method for Determination of the Composition of Unprocessed Municipal Solid Waste; and UNEP waste characterization method.

Sorting processes equipment and their classification

Sorting process is a very complex set of machines that need to operate in a specific sequence and speed in a synchronous way that leads to achieving maximum output. Sorting processes can be classified into different categories based on the chosen criteria. When target SRM physical and mechanical properties are used as the classification criteria, sorting processes are divided into 4 groups: 1) sorting by size; 2) sorting by density/weight; 3) sorting by magnetic properties; and 4) sorting by others, e.g., colour. If the level of mechanisation and reliance on labour force in recovering SRM are the criteria then sorting processes can be divided into manual, automatic and combined processes. Automated sorting techniques can be categorized into two groups (Gundupalli et al., 2016):

d direct sorting, using techniques that utilise material properties like magnetic susceptibility, electrical conductivity, and density for heavy media separation by applying external fields like magnetic, eddy current and gravity;

e indirect sorting, with techniques that employ sensors to detect the presence and often the location of recyclables in the MSW stream so that automated machines or robots can be engaged to sort out the detected SRM. All sorting processes that depend on machines are built to deal with material properties. The failure to do so maybe either related to machine design and calibration or – most likely – incomplete set of information related to input MSW morphology.

Current MA methods

All the current MA methods focus on the quantitative aspect, where results are submitted in the form of tables with content percentage of each SRM type. In some cases, the reports are augmented by implementing SRM fraction sorting into different levels like fractioning organic waste into food waste and gardening waste levels, and plastic into PET, HDPE, PVC, LDPE, PP, PS and other resins (Edjabou et al., 2015). Using a sieving stage to separate the 20 mm fine material from the 200 mm fraction then, conducting the MA study in closed spaces to prevent evaporation are other novelties proposed to increase the accuracy and output information value (Ciuta et al., 2015). Another method recommended is that sorting the representative sample should continue manually until the maximum size of the remaining waste particles is approximately 12.7 mm (ASTM, 2003). Drying an MSW sample before conducting MA is implemented in some methodologies to improve the result accuracy (Wavrer, 2015). Some research has proposed further mixing between sample reduction rounds, until a representative sub sample of 100–200 kg remains, and then conducting SRM fractioning and sub-fractioning (Gaillot et al., 2005). Stratification of the in-homogenous parent population into homogenous subs, where the level of sampling is concerned with the position along the waste management process at which waste samples are taken for subsequent analysis, is another addition that has been proposed to reach higher levels of accuracy of MA; the level of stratification that was proposed went down to details where strata was created based on collection vehicle type, bin volume, specific weight of household/commercial, and specific number of residents who generated relevant waste (European Commission, 2004). Another example of seeking better outcome quality from MA is to put more efforts in setting the geographical boundaries with a clear definition and demarcation of geopolitical and administrative boundaries, and setting comprehensive procedures for MSW data collection, analysis, and presentation (United Nations Environment Programme, 2009).

Despite having these various novelties aiming at creating the most comprehensive set of data in the MA report, we observe challenges in the existing MRF designs to achieve targeted recovery rates and meet the market demand in regard to SRM quality. In many case studies conducted in the EU, it was observed that SRM components were still present in significant quantities in the residues of mixed MSW, resulting from sorting processes, and recovery rates in some of these facilities did not exceed 10.5% (Cimpan et al., 2015). Studies focused on MRF output contamination levels showed as high as 18.2% contamination level in plastics recovered from mixed MSW (The Waste and Resources Action Programme, 2009). Another case in a single stream MRF revealed that 73.29% of all the grit, fines, and sweepings were still present in the recovered glass, which allowed only 70.16% of the mixed glass to be recovered (Damgacioglu et al., 2019). The successful use of automated sorting lies in determining how each material stream responds when introduced to certain technologies or techniques. The key is choosing the right technology at the right stage in the sorting process to cause a single material stream to behave differently than the others (WRAP, 2006), and in this regard, all existing MAs seem to come short to predict this behaviour by focusing on quantitative evaluation. In one of the case studies, it was found that more than a third of the rigid packaging material feed was falsely discharged into the wrong stream as they easily pass through the screen lining of 65 mm × 65 mm due to the fact that they are not uniform, either in shape or in surface (Feil et al., 2017). The lost quantity can be even higher, knowing that screens opening sizes may sometimes be between 65–80 mm (Jansen et al., 2015). Analysis conducted to evaluate the efficiency of packaging waste MRF showed that during the ballistic separation stage in case rigid hollow-shaped plastic components have been compressed during collection or processing, the chance that they will be lost to the flexible output stream increases. The results of the screening stage in the same study showed that SRM from the input was found in all sorting line sub-streams. It was also observed that light fraction separated in the air separation stage was found to contain all types of rigid plastics beside the 40% of the target light film (Jansen et al., 2015). Current MA methods do not help to prevent any of the above cases from happening because SRM sizes and dimensions distribution are not part of MA deliverables.

MRFs in the United Arab Emirates (UAE)

UAE stands tall amongst other countries in the Middle East region for being an icon that represents the quality of life and prosperity. This lifestyle was accompanied by a spike in the MSW generation rates. The MSW generated in the Emirate of Abu-Dhabi – the capital of UAE – in 2019 increased by almost 41% to reach 1.793 million tons compared with 1.272 million tons in 2012. MSW generated per capita in Abu-Dhabi (AD) remains one of the highest globally and was reported at 1.76 kg/day in 2018 compared to 1.5 kg/day in 2012 (Center of Statistics-Abu Dhabi, 2018). The latest statistics show that UAE generated 6.271million tons of household waste in 2018 (MOCCAE, 2020). UAE is implementing the mixed MSW collection method. Separate initiatives are implemented to segregate waste at source, but these initiatives have an insignificant impact and do not make any statistical change. During the period

Table 1. *MRF facilities in the UAE (author's research,2020)*

Emirate	Number of MRFs	Ownership	Current status of MRF's
Abu Dhabi	1	Government	Not operational
Dubai	5	Private	Two facilities not operational
			Two facilities partially operational
			One facility fully operational
Sharjah	1	Public Private Partnership	Fully operational
Um Al-Quwain	1	Government	Partially operational
	1	Public Private Partnership	Not operational
Ajman	1	Government	Fully operational
Ras Al-Khaimah	1	Government	Fully operational

from 2012 to 2018, UAE built 11 MRFs all over the 7 Emirates (Table 1). Despite the early start, compared with other neighbouring countries, to address the concerns related to the low MSW recovery rates and increasing quantities disposed of, none of the built facilities managed to come close to their designed recovery rates. Moreover, three facilities were closed down and another one was forced to dismantle most of the automated sorting equipment and switch to manual sorting to reduce maintenance and power consumption costs, while two others operate on selected quantity of MSW to maintain a healthy financial position. The total quantity of treated MSW in the UAE in 2019 did not exceed 21% of the total generated (MOCCAE, 2020).

The disappointing recovery rates and financial results of these facilities cast doubts on the reliability of the MA studies provided prior to designing the sorting processes, and the quality of these facilities design itself. Knowing that all MAs were provided by reputable organizations and most MRFs were designed by experienced companies before securing the investment approvals, it can be assumed that all these models had a common flow that was the initial potential SRM recovery assumptions provided in those MA studies.

Methods

In this research, 8 representative samples were randomly selected from mixed MSW that was delivered to Sharjah Environment company "Bee'ah" in Sharjah city, UAE. The average sample weight was 1103 Kg. Each sample underwent multi-stage detailed analysis. Each MSW sample was sorted into two portions: material delivered in sealed bags (bagged or B) and material delivered in loose condition (loose or L). Each portion was further analysed separately. All bags from B portion were teared open and all of their contents were fully extracted, and the empty bags formed as a separate component called "low density polyethylene (film LDPE)". Next, each sample of L and B portions was separately screened to sieve out fines with the size less or equal to 50 mm (fines). For this purpose, a perforated steel sheet was prepared with calibrated 50 mm diameter round holes (Fig. 1a). Sample material was dropped in portions on the perforated sheet which was shaken to ensure proper screening. Fines were collected from the clean plastics sheet that was placed under the screening table for this purpose. The fines were weighed and kept aside. After that, all components above 50 mm were segregated into different size groups, 51–100 mm, 101–150 mm, 151–200 mm, 201–250 mm, 251–500 mm, and 501–1000 mm. To determine the component size groups, steel boxes with relevant calibrated dimensions were fabricated (Fig. 1b) and each component was considered of the size of the box where it could better fit in. The density of each component size group was measured for B and L portions separately. For this purpose, a steel box with controlled dimensions of 1000 mm x 1000 mm x 1000 mm was fabricated (Fig. 1b). The components of one size group and of the same portion were placed in the box, and then the weight of this box and the material level in the box ware measured. Material density then was calculated for each component size group as follows:

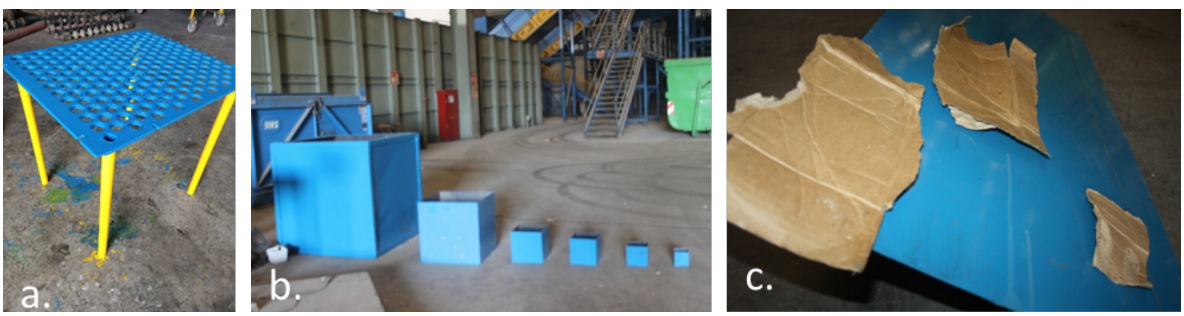
$$Material\ density\ (\frac{Kg}{m^3}) = \frac{material\ weight\ (box\ weight\ after - box\ weight\ before)}{material\ hight\ in\ the\ box \times (box\ internal\ length)^2} \quad (1)$$

There is no evidence that component density per component were ever implemented in any previous MA. The following step was to obtain a sample from each component size group and send it for a moisture content test. Similar components of each size group were divided into two groups, two-dimensional (2D) and three- dimensional (3D) components. To determine the dimension of the components, a flat plate was fabricated and fixed with 33 degrees inclination (Fig. 1c). Each sample component was dropped to free fall on the plate from a height of 300 mm to 500 mm. The component was considered as 3D if it rolled or bounced back upon the impact; otherwise, it was considered 2D. This method was never implemented in any previous MA that the author is aware of.

To present the results in a simple way, all the SRM content percentages were converted into tons per day, considering 1200 ton per day input of MSW. Production per year was considered 330 working days. The SRM component sales prices were calculated based on average SRM sales prices in Europe in 2019. These prices were found to be as follows: 121 Euro/ton for ferrous steel, 118.5 Euro/ton for cardboard, 385 Euro/ton for high density polyethylene, 118.5 Euro/ton for paper, 210 Euro/ton for PET containers, 850 Euro/ton for aluminium used beverage cans, 850 Euro/ton for aluminium foil, 110 Euro/ton for tetra pack, 55 Euro/ton for glass and 385 Euro/ton for polypropylene (Eurostat, 2020). The extracted material from bags was screened and each component with the size above 50 mm was divided into the determined size groups; then, the anticipated tonnage of SRM to be produced and the sales revenue to be generated per year were calculated as mentioned in point 1 and recorded in a separate table. Each size group component was placed in the steel box (Fig. 1b) and the density was measured and recorded. All the components of different size groups were divided into 7 density categories between 0 kg/m^3 and 400 kg/m^3 (Table 6). A representative sample was obtained from each size group component to test the dimension and configuration using the inclined plate.

Simultaneously, a representative sample was obtained from each size group to measure the moisture content in the lab. The results were communicated to traditional customers in the market to explore whether products quality is acceptable and to negotiate the discounts requested. The expected annual revenue from recovery and sales of B portion SRM was calculated in a separate table. An exception was made for L portion as a moisture content test sample was obtained from the portion without referring to the size group, because L portion is delivered in loose mix and, thus, it is expected that moisture migrates between its components during collection, transportation, and handling. The density and dimensional distribution results of all the sampled components were recorded in separate tables as well. Finally, a conclusive table was prepared to demonstrate the potential recovery and revenue to compare with those generated from a traditional MA study.

Fig. 1. *a. perforated sieving sheet; b. size and density boxes; c. inclined sheet*



Results

The traditional MA results and potential revenue anticipated from SRM in the sorting process (Table 2) showed that delivered MSW to Bee'ah MRF at the rate of 1200 ton/day would generate 16.992 million Euro per year from SRM sales. LDPE film (mainly plastics bags) has no market value due to its low quality and high recycling cost. The table shows that the highest value would be generated from the sales of rigid high density polyethylene (HDPE), all types of PET, and polypropylene plastics containers (4,742,300 Euro), then cardboard (3,892,800 Euro/year) followed by paper (2,948,300 Euro/year), and finally, ferrous steel (FS) and aluminium used beverage cans (UBC) with an anticipated value of 2,616,800 Euro/year.

Table 2. *Traditional MA results and anticipated income from SRM sales*

Component	%	Ton/day	Expected SRM sales revenue, (Euro/year)
Film (LDPE)	9.5	114	–
Ferrous Steel (FS)	1.9	23	907,900
Cardboard	8.3	100	3,892,800
High density Polyethylene (HDPE)	0.9	11	1,382,200
Paper	6.3	75	2,948,300
PET transparent	2.0	24	1,666,200
PET green	0.2	2	150,800
PET coloured	0.03	–	22,600
Aluminium used beverage cans (UBC)	0.5	6	1,708,900
Foam	0.5	6	–
PS	2.5	30	–
Aluminium foil	0.6	7	1,892,000
Tetra pack	0.5	6	209,300
Wood	2.4	29	–
Glass	3.2	38	691,100
Textiles	3.8	46	–
Polypropylene (PP)	1.0	12	1,520,500
Polyvinylchloride (PVC)	0.1	1	–
Stones	2.6	32	–
Footwear / wires /ropes	0.9	10	–
Others	4.6	55	–
Fines	47.7	573	–
Total	100	1,200	16,992,700

When initial segregation was completed, it was found that 13.79% of the MSW belonged to the B portion, whereas the remaining 86.21% belonged to the L portion. The distribution of B portion component size (Table 3) showed that valuable SRM falls in the size category from 100 mm to 250 mm (around 85.5%). It also showed that bagged MSW would bring 8.9% of the total sales revenue calculated in the traditional MA provided in Table 2, which puts the feasibility of investing in bag opening machines as part of MRF design in doubt as the value returned is low. Moreover, the high percentage of L portion indicates the severity of the mechanical damage, caused to the MSW during its transportation and handling that led to having majority of waste bags been torn open.

Due to screen disc spacing design mentioned earlier, it was assumed that 100% of the fines, and 50% of 50–100 mm components will pass between the discs and will be lost as fines and residues. The results of moisture content analyses were discussed with customers and final discounts were agreed per component; thus, the revised SRM sales discounts were concluded (Table 4). The category size 0–50 mm was removed from the table because it had 40% moisture content and it was mainly of organic waste, broken glass, and trash. B portion SRM had extremely high moisture content which varies from one component to another and the highest was found in absorbent materials like cardboard and paper.

The fact that oil and food were part of moisture content formation made the recyclers resistant to accept the SRM at market prices and in some cases to completely reject it (100% discounted in the table with “R”). The final

Table 3. *MA results conducted on portion B and possible revenue from SRM sales*

Component	Size group					ton/year	Sales revenue (Euro/year)
	50–100 (ton/day)	101–150 (ton/day)	151–200 (ton/day)	201–250 (ton/day)	251–500 (ton/day)		
Film (LDPE)	0.55	6.57	4.93	6.57	1.54	6,700	0
FS	–	–	–	0.55	0.36	300	36,200
Cardboard	–	0.22	–	1.64	0.77	900	102,900
HDPE	–	0.33	–	0.44	0.06	300	105,200
Paper	0.33	–	0.55	1.64	0.12	900	103,300
PET transparent	–	–	–	0.77	–	300	53,200
UBC	0.55	0.55	0.55	0.55	–	700	613,800
Foam	–	0.22	–	-	–	700	–
PS	–	1.10	–	0.33	–	500	–
Aluminium foil	–	–	1.10	0.55	–	542	460,900
Tetra pack	–	0.22	–	–	–	72	8000
Wood	–	–	–	–	0.77	253	–
Textiles	–	–	0.55	1.10	1.23	948	–
PP	–	–	–	0.22	–	72	27,800
Others	0.76	17.31	8.33	14.02	2.72	14,236	–
Fines	2.53	21.02	34.21	15.35	11.75	28,004	–
Total	4.71	47.53	50.20	43.73	19.31	54,609	1,511,300

Table 4. *Revised sales revenue of B fraction*

	51–100			101–150			151–200			201–250			251–500			Total
	Moisture (%)	Discount (%)	Sales revenue (thsd. €/year)	Moisture (%)	Discount (%)	Sales revenue (thsd. €/year)	Moisture (%)	Discount (%)	Sales revenue (thsd. €/year)	Moisture (%)	Discount (%)	Sales revenue (thsd. €/year)	Moisture (%)	Discount (%)	Sales revenue (thsd. €/year)	Sales revenue (thsd. €/year)
Film (LDPE)	36	–	–	35	–	–	33	–	–	34	–	–	18	–	–	–
FS	–	–	–	–	–	–	–	–	–	45	30	15	30	25	11	26
Cardboard	–	–	–	35	R	–	–	–	–	33	R	–	20	50	15	15
HDPE	–	–	–	23	25	31	–	–	–	17	20	45	15	20	6	82
Paper	35	R	–	–	–	–	32	R	–	29	R	–	29	R	–	–
PET transparent	–	–	–	–	–	–	–	–	–	17	20	67	–	–	–	67
UBC	14	20	62	9	10	139	18	20	123	12	15	131	–	–	–	455
Foam	–	–	–	11	–	–	–	–	–	–	–	–	–	–	–	–
PS	–	–	–	11	–	–	–	–	–	15	–	–	–	–	–	–
Aluminum foil	–	–	–	–	–	–	34	50	154	35	50	77	–	–	–	231
Tetra pack	–	–	–	18	20	7	–	–	–	–	–	–	–	–	–	6
PP	–	–	–	–	–	–	–	–	–	15	15	24	–	–	–	24
Total																907

revenue figure would drop by 40% to as low as 907,217 Euro compared with 1.511 million Euro that was initially anticipated (Table 3).

Identical steps were followed to identify the realistic revenue that would be generated from recovering SRM in L portion (Table 5). The results showed that anticipated SRM sales revenue would be around 5.9 million Euro per year. Moisture, organics, and oil contamination issues were evident for this portion as well. In 0–50 mm components, the moisture content was 38% and was totally rejected and removed from the table. Paper was totally rejected by recyclers. Cardboard and liquid packaging had very high moisture content and their prices were discounted accordingly. Non-absorbent metal containers would be sold with discounts between 15% and 20% except for the aluminium foil, where a 50% discount was claimed due to the fact that foil was used to package meal leftovers which led to very high moisture and oil contamination levels. The adjusted revenue from L portion dropped down to 5.865 million Euro. From tables 6 and 7, the final adjusted revenue from both portions becomes 6.574 million Euro, which is 71% less than the anticipated figure earlier (Table 2).

The density analysis conducted for each size group components of B and L portions (Table 6) revealed that components of one type of SRM can fall in different density groups. This scattered distribution can be explained by the variations of the same component type in sizes, moisture contents, configurations, and other factors. Thus, the attempt to calibrate air separation equipment to sort out a specific component like plastics bags based on their density would lead to ejecting 12 other SRM types of similar density. The only consistent components were glass, stones, shoes, wires, and ropes. Further visual analysis helped to identify three factors behind this disperse:

a Individual behaviours like leaving liquids in beverage bottles, then closing them, flattening plastics containers, tearing paper and cardboard, and crumpling components before disposing of them into the waste bin

b Logistics, including multiple handling stages led to tearing most of the plastics bags open, damaging paper and cardboard, breaking glass containers and in many cases, flattening plastics containers. The MSW in Sharjah is transferred in compactors from the city to a transfer station where it is dumped and temporarily stored; then, it is loaded by wheel loaders in haulage trucks to be sent to the MRF where it is dumped on the tipping floor, to be loaded into the feeding conveyors by wheel loaders.

c Water and oil content in the food waste and leftover beverages led to distributing moisture over all MSW components. Not only did this lead to changing the weight of the components and consequently, their density, but also encouraged the degradation of paper and cardboard and facilitated creasing and crumpling which also led to the density alteration.

Table 5. *Revised sales revenue of L portion*

	51–100			101–150			151–200			201–250			251–500			501–1000	Total
	Moisture (%)	Discount (%)	Sales revenue (thsd. €/year)	Moisture (%)	Discount (%)	Sales revenue (thsd. €/year)	Moisture (%)	Discount (%)	Sales revenue (thsd. €/year)	Moisture (%)	Discount (%)	Sales revenue (thsd. €/year)	Moisture (%)	Discount (%)	Sales revenue (thsd. €/year)		Sales revenue (thsd. €/year)
Film (LDPE)	–	–	–	27	R	–	27	R	–	27	R	–	27	R	–	Only Film (LDPE), 27% moisture content, all rejected	–
FS	17	20	130	17	20	139	17	20	157	17	20	37	17	20	87		550
Cardboard	27	50	186	27	50	44	27	50	340	27	50	277	27	50	108		955
HDPE	16	20	111	16	20	201	16	20	217	16	20	55	16	20	217		800
Paper	29	R	–	29	R	–	29	R	–	29	R	–	–	–	–		–
PET transparent	17	20	986	17	20	267	–	–	–	–	–	–	–	–	–		1.252
PET green	14	20	12	14	20	97	–	–	–	–	–	–	–	–	–		109
PET colored	12	20	9	–	–	–	–	–	–	–	–	–	–	–	–		9
UBC	11	15	465	–	–	–	–	–	–	–	–	–	–	–	–		465
Aluminium foil	33	50	159	33	50	181	–	–	–	–	–	–	–	–	–		340
Tetra pack	13	15	60	13	15	52	–	–	–	–	–	–	–	–	–		112
Glass	7	15	136				–	–	–	–	–	–	–	–	–		136
PP		15	131	16	15	260	16	15	207	16	15	205	16	15	335		1.138
Total																	5.865

Table 6. *Component densities*

	50-100		101-150		151-200		201-250		251-500		501-1000	
	B	L	B	L	B	L	B	L	B	L	B	L
Film (LDPE)	51–100		0–50	51–100	0–50	51–100	0–50	51–100	0–50	0–50		51–100
FS		151–200				51–100		151–200		201–300		0–50
Cardboard		101–150	0–50	101–150		51–100		51–100		0–50		
HDPE		51–100	51–100	0–50		51–100		101–150		0–50		
Paper		101–150		151–200		101–150		201–300				
PET transparent		51–100	101–150	0–50								
PET coloured		51–100		51–100								
PET coloured		201–300										
UBC		51–100										
Foam		0–50	51–100	0–50				0–50				
PS		51–100	101–150	0–50								
Aluminium foil		101–150		101–150								
Tetra pack		51–100	101–150	101–150								
Wood				151–200		201–300						
Glass		301–400										
Textiles				51–100	51–100	51–100	151–200	51–100	51–100	101–150		101–150
PP		51–100		0–50		0–50		0–50		0–50		51–100
PVC		151–200		51–100								
Stones		400+		400+		400+						
Footwear/wires/ropes				400+		400+		400+				
Others	201–300	201–300	151–200	400+								

- 0–50 kg/m^3
- 51–100 kg/m^3
- 101–150 kg/m^3
- 151–200 kg/m^3
- 201–300 kg/m^3
- 301–400 kg/m^3
- 400+ kg/m^3

Table 7. *Component configurations*

Production (ton/day)		L	B	L	B	L	B	L	B	L	B	L	B	L
		0–50		51–100		101–150		151–200		201–250		251–500		501–1000
Film (LDPE)	2D				0.6	33.7	6.6	10.9	4.9	21.2	6.6	16.9	1.5	11.39
	3D													
FS	2D	0.54				2.71		4.36			0.2		0.1	
	3D			8.16		1.64		0.54		1.16	0.4	2.72	0.3	
Cardboard	2D	16.3		15.6		22.3	0.2	17.4		14.1	1.5	5.53	0.8	
	3D	2.2		3.44							0.1			
HDPE	2D			1.1		0.73	0	1.26			0.2		0	
	3D	1.09		1.08		1.25	0.3	0.87		0.54	0.2	2.13	0.1	
Paper	2D	23.29		14.7	0.2			5.09	0.6	10.2	0.6		0.1	
	3D	3.19		2.98	0.2						1		0.1	
PET transparent	2D			9.43		3.35					0.5			
	3D	0.69		8.35		1.46					0.3			
PET green	2D			0.11		0.11								
	3D			0.33		1.63								
PET coloured	2D			0.22										
	3D			0.11										
UBC	2D			1.9	0		0.2		0.2		0.3			
	3D			2	0.6		0.3		0.3		0.2			
Foam	2D	0.56		2		0.14				1.27				
	3D	0.5		1.01		0.1								
PS	2D	5.93		10.2		3.59								
	3D			7.25		1.99	1.1				0.1			
Aluminium foil	2D													
	3D	1.54		2.27		1.29			1.1		0.5			
Tetra pack	2D			3.15		1.69	0.1							
	3D			0.7			0.1							
Wood	2D	5.1		7.54		5.81		1.77					0.3	
	3D			6.09		1.92							0.5	
Glass	2D	16.46												
	3D	3.95		17.6										

Table 7. (continued)

Production (ton/day)		L	B	L	B	L	B	L	B	L	B	L	B	L
		0–50		51–100		101–150		151–200		201–250		251–500		501–1000
Textiles	2D					4.13		1.59	0.6	4.21	1.1	18.9	1.2	14.26
	3D													
PP	2D			2.42		1		0.92		1.9	0.1	1.9		
	3D					1.41		1			0.1	1.2		
PVC	2D													
	3D			0.57		0.43								
Stones	2D	3.82		7.18		3.2		3.56						
	3D	2.21		3.8		8.23								
Footwear/wires/ropes	2D									2.62				
	3D					4.23		3.15						
Fines	2D	488.1												
	3D													
Others	2D													
	3D			1.64		10.2								

The configuration analysis results (Table 7) showed that components of one SRM type may be delivered to MRF in both 2D and 3D configurations. The results also made clear that 2D/3D ratio for any selected components of the same SRM type might vary from one size group to another. This ratio depends on the same mechanical forces, analysed earlier. Considerable quantity of rigid containers was found to be flattened, but the most affected component was found to be water bottles (55.4% of PET was found flattened), and then UBC (44.8% of aluminium cans were found flattened). Only plastic bags were found consistently in 2D shape, which justifies the ballistic separation technique deployment to sort them out; however, all other types of flat SRM would be expected to end up in this stream in different percentages as well.

The outcome of the proposed MA approach in this research made it possible to forecast SRM behaviour in different sorting stages and predict SRM possible losses (Table 8). After opening all bags and sieving out the fines and organic wastes, including SRM of similar sizes, a standard mechanical sorting process would operate in the following sequence:

a Air separation to split the stream into light and heavy material. Light stream is usually expected to be dominantly formed by plastic bags, paper, and cardboard.

b Ballistic separation to segregate the material according to dimension and configuration. It is usually used to split the heavy fraction into 3D rigid containers and remaining 2D plastic bags, and minor quantities paper, and cardboard.

c Optical and other sorting mechanisms to recover rigid containers by type from 3D fraction.

Magnetic separators are installed in different stages to ensure high rates of FS removal.

The attempt to simulate the sorting results (Table 8) led to conclude the following:

a All light fraction that would be sorted out at the air separation stage is considered to be residue with zero value. This stream is mainly plastic bags (47.2%) with no value but contains cardboard (18.6%) and negligible quantities of different other SRM components. The investor may decide to deploy additional mechanical, automatic or manual sorting processes

Table 8. *Anticipated SRM revenue per day at each sorting stage*

		B portion		L portion	
Sorting stage	2 D stream Component	Production (ton/day)	Revenue (€/day)	Production (ton/day)	Revenue (€/day)
Air separation	Film (LDPE)	19.88	0	94.07	0
	FS			4.9	
	Cardboard	0.22		37.08	
	HDPE	0.33		5.35	
	PET transparent			13.7	
	PET green			1.96	
	UBC			1.95	
	Foam	0.22		3.02	
	PS			14.33	
	Tetra pack			1.93	
	Textiles	1.78		9.93	
	PP			10.54	
	PVC			0.43	
2D fraction, ballistic separation	FS	0.3	23.69	0	11,596.88
	Cardboard	2.29	632.53	30.1	
	HDPE	0.2		0.73	
	Paper	1.56		33.54	
	UBC	1.43			
	PET coloured			0.11	
	Tetra pack			2.67	
	Wood	0.27		11.33	
	Textiles	1.1		33.21	
	PP	0.12			
	Stones	0		10.33	
	Footwear/wires/ropes	0		5.76	
3D fraction, ballistic separation	FS	0.61	48.16	7.96	693.46
	Cardboard	0.12	9.8	1.72	0
	HDPE	0.3	83.16	1.79	496.57
	Paper	0.71	–	3.89	0
	PET transparent	0.77	116.42		
	PET coloured			0.05	8.14
	UBC	0.49	318.62		

Table 8. (continued)

		B portion		L portion	
Sorting stage	2 D stream Component	Production (ton/day)	Revenue (€/day)	Production (ton/day)	Revenue (€/day)
	Aluminium foil	1.64	627.3	2.42	926.22
	Tetra pack	0.22	17.42	0.94	46.75
	PS	1.42	0		
	Wood	0.5	–	4.98	
	PP	0.1	29.45		–
	Glass			8.84	371.84
	PVC			0.29	–
	Stones			10.15	–
	Footwear/wires/ropes			4.23	–
	Others			11.04	

to reclaim the cardboard and other selective SRM at additional cost but, the financial model would mostly show adverse results.

b The produced 2D mix, resultant from ballistic separation, was accepted by clients at 50% of paper or cardboard market price, but not to recyclers. The buyer of this mix would further sort it to recover cleaner SRM and generate profit. The investor, however, may choose the deployment of manpower to manually sort this mix out or to invest in more mechanical and automated sorting equipment, but the financial model would mostly show adverse results.

c FS is the only component that would be fully sorted out with relatively cheap and effective magnet separation equipment.

d By default, the 3D fraction, resultant from the ballistic separation stage, is expected to be mostly rigid and hollow beverage containers. 3D plastics would have high market value when sorted out according to polymer types using optical sorters, while UBS and foils would be usually sorted out by Eddy Current equipment, and FS would be sorted out using magnetic separators. The efficiency of this sorting stage, considering the mix, was assumed 90%.

Consequently, the final SRM quantities and sales revenues were compiled (Table 9) based on all the quantitative, qualitative, and financial analyses provided in this research. The updated calculations in accordance with the proposed MA showed a drop-in sales revenue to as low as 5.325 million Euro per year compared with the initially expected sales revenue of around 16.992 million Euro per year (Table 2).

Table 9. *Final calculations of reclaimed SRM and annual revenue based on proposed MA*

	Ton/ day	Sales revenue (€/day)	Sales revenue (€/year)
SRM mix	134.76	12,229.4	4,035,700
FS	8.78	765.3	252,600
Cardboard	1.83	150.5	49,700
HDPE	2.06	579.7	191,300
PET transparent	0.69	116.4	38,400
PET coloured	0.05	8.1	2,700
UBC	0.44	318.6	105,100
Aluminium foil	3.90	1,553.5	512,700
Tetra pack	1.14	96.9	32,000
PP	0.09	29.5	9,800
Glass	8.84	371.8	122,700
Total	1,200	16,220	5,352,600

Discussion

This research did not consider factors like seasonality and was conducted for limited number of samples. More samples with improved stratification might give more confidence in the results; however, the approach and the data interpretation would remain the same. Despite the fact, that all analyses were conducted in enclosed area, minor losses in weight were observed and these losses were distributed among the components proportionally. It is believed that such distribution would not significantly affect the study output. The losses during screening, assumed in this research, are based on screen opening size between 65 mm and 80 mm but may slightly be reduced when special design precautions like squared shape or sleeved round holes are designed for trommel drums. It is also important to mention that density separation efficiency is dependent on the components surface areas as well; wind shifters, air knifes, and other techniques operate best when the ratio between the largest and smallest objects being fed into the density separator is relatively narrow (Gitschel, 2017). So, dedicating specific analysis in this direction may help to better predict SRM behaviour at the air separation stage.

The findings in the research revealed similar MRF efficiency challenges that were highlighted in previous studies. The proposed MA methodology was able to predict the rejection of SRM by recycling facilities due to moisture content and contamination levels highlighted by Damgacioglu et al. (2019) and Ciprian et al. (2015). This research made it possible to estimate, in advance, the losses caused by the false discharge of 3D material in the 2D stream that was indicated by Feil et al. (2017) as well. The main advantage of the proposed MA method, however, is the possibility to raise red flags to indicate all the SRM quantitative and qualitative risks and to alert equipment designers about the efficiency risks on the early stages of MSW recovery business plan formation while other MA methods fail to do so.

Conclusions

In this research, it was concluded that the recovery stage forms the crux of an MSW avoidance strategy in the EU. It also revealed that a professionally designed and operated sorting process can turn mountains of MSW into valuable secondary resources to fuel circular economy. The research highlighted the unacceptable situation with MSW recovery in the UAE while generation per capita is peaking. It became clear in this study that current MRF projects in the UAE fail to sustain due to a common fault that is related to the initial revenue generation model. Current MRF projects in the UAE built their business model based on traditional waste composition analysis reports that were proven in this research to be misleading.

The research revealed that current waste morphology analysis falls short to meet the investors' demand for comprehensive set of data that would help to build a cohesive MSW sorting business plan because all existing methods lack the descriptive part related to SRM physical and mechanical properties needed by the sorting equipment designer most. The analysis found that traditional MSW morphology also fails to forecast MRF revenue losses due to unsatisfying SRM quality. Based on the analytical determinations of this research, it was proven that any mixed MSW sorting business plan, based on traditional waste composition analysis, is mostly to face colossal financial losses.

In our specific case, the mechanical sorting line would end up generating only 25% of the revenue that was initially planned based on the traditional morphology analysis; any additional revenue would require deployment of more equipment and manpower, which would boost the cost of sorting. Most of the revenue losses were related to SRM moisture content as well as size and dimensions distribution. All these factors led to the changes in SRM component response to several mechanical sorting solutions and, eventually, caused a considerable amount of SRM components to end up in the residue or in a low value mix stream.

The benefits of implementing the proposed morphology analysis method can be summarized as follows:

e This method works to predict the SRM losses due to low sorting efficiency at the early design stage, which gives the chance to reconsider or seek alternatives at the investment decision-making stage.

f The cost of reluctance to implement source segregation can be easily measured by using this method, which could greatly assist in convincing governments to shift from a mixed MSW collection method to improve SRM value and attract investors to build successful MRF projects and supply more SRM to the market at a competitive price.

g Using this method can be an efficient tool to tackle those MSW generators behaviours that cause significant damage in the SRM value chain as this method makes it possible to quantify the adverse effects, caused by mixing, tearing, crumpling and flattening SRM components. Moreover, the proposed method can be conducted before and after changing a specific behaviour to evaluate the potential effect before moving to change another.

This method could bring more value if it could be automated to incorporate the sorting machines parameters in an artificial intelligence system that could recommend the best sorting equipment arrangement in MRF based on the recovery rate planned and the number of SRM components to be produced. The system could identify the losses due to material quality and recommend various changes, based on the SRM physical and mechanical properties.

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