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Plastics Waste and Circular Economy. Low-Density PolyEthylene recycling feasibility study

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Abstract
Circular economy, nowadays, is an inherent part of the EU economic development. Plastics waste management is an enormous unutilised potential awaiting exploitation if a new efficient system of collection, transport and recycling technology can be put into place. This paper serves to analyse the current situation and trends in plastic waste management in the European Union. It renders a discussion on the optimum balance of plastics in the context of a circular economy encompassing the association between urban plastics mining and efficient plastic waste collection processes- its aggregation, sorting, processing, energy recovery and outputs of recycling materials. The paper focuses on Low-Density PolyEthylene (LDPE) plastics accounting for more than 17 percent of produced plastic in Europe. Described and evaluated are the available LDPE processing technologies with accompanying analysis of a newly developed technological line for LDPE processing. Additionally, the complex process of urban mining of LDPE plastics is discussed and the circular economy for LDPE films is presented.

Keywords
plastics, plastics waste, LDPE film, circular economy, regranulation line.

Introduction

Polyethylene is the largest polymer produced globally (over 90 million metric tons per annum). Since its discovery in 1933, it has evolved into a material critical to modern life. Improved polymer performance based on new catalyst and application technologies have made it possible to have diversity of use that we see today. It is an essential material to power transmission, food packaging, consumer goods, electronics, household goods, industrial storage, transportation industries, etc. [1-3]. In year 2013 US EPE estimates that only less than 6% of this material is being recycled.

The oldest type of Low-Density PolyEthylene (LDPE) is a soft, tough and flexible polyethylene used in strong and flexible consumer items like screw caps and lids. For a long time already, it is also used as insulation material. At present, the most popular application is film, from which carrier bags, packaging material and agricultural plastics are made.

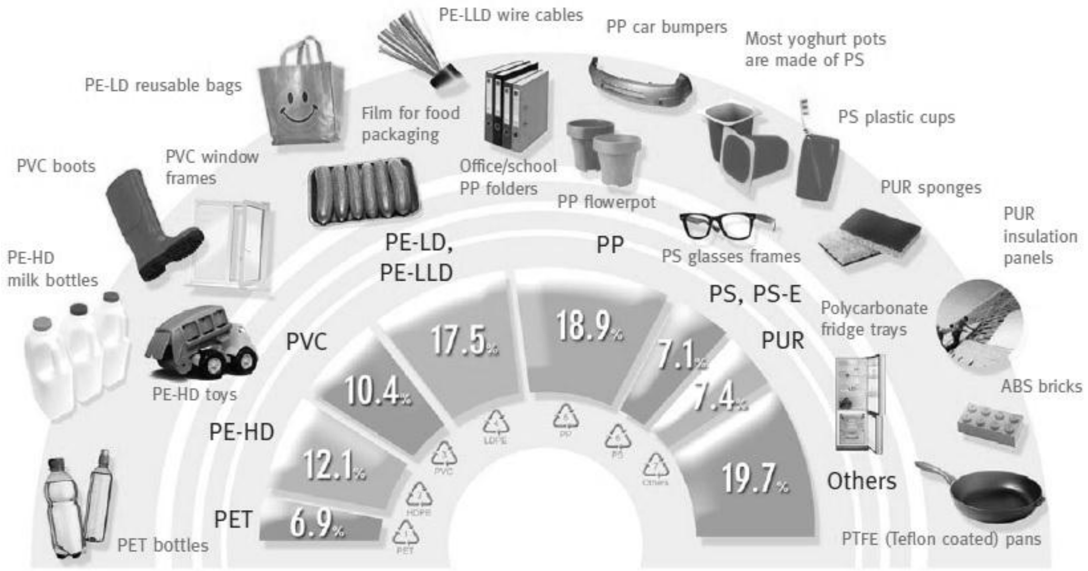

Fig. 1 Requirements with respect to plastics in Europe in 2013. Source: [3]

LDPE is widely used and popular. Distribution patterns show that LDPE waste has 21% share in packaging and 68% even in the agricultural waste stream [4]. This commodity seems to be ideal in order to launch the circular economy strategy as soon as possible. The reasons are as follows:

- Of relevance is the fact that the general community as well as those who directly use LDPE has certain knowledge of this type of waste.
- A considerable advantage is that products from recycled LDPE waste can be widely used for example in agriculture film, as plastic bags for waste collection or in many further applications.
- This type of waste is dumped at landfills in large quantities. If placed incorrectly and compacted in continuous layers, it creates a kind of false sealing preventing landfill water to penetrate into the lower layers of the landfill, causing water to flow uncontrolled out of the landfill body.
- In the mechanical and biological treatment facilities for mix waste there is very limited opportunity to separate these waste types consistently as there are major problems already at the first sorting level (jamming, winding).
- And, of course, the key argument is that polyethylene is the most widely used of all plastics (see Fig. 1).

Andreoni et al. [5] published the waste policy scenario analysis for EU-27, where they suggested high potential for reusing waste polyethylene. The results show that the socio-economic and environmental benefits can be generated across the EU by implementing the best practice scenario. In particular, estimations show a possible reduction of 4.4 million tonnes of non-recycled PE waste, together with reduction of around €90 million in waste management costs by 2020 for the best practice scenario versus the business as usual scenario. An additional 35 622 jobs are also expected to be created. In environmental terms, the quantity of CO_2 equivalent emissions could be reduced by around 1.46 million tonnes and the net energy requirements are expected to increase by 16.5 million GJ as a consequence of reduction in the energy produced from waste. Van Eyen et al. [6] analysed the plastics household for Austria in 2010 through material flow analysis to track the flows and stocks throughout the system, from production of the primary polymers up to and including the treatment of the produced waste streams. About 1.1 million tonnes of primary plastics were produced in Austria in 2010, and with

additional trade of polymers and semi-finished and final products, 1.3 million tonnes of plastic products are used for Austrian consumption. This consumption is distributed over ten consumption sectors, of which packaging (24%), non-plastic products (20%), building and construction (18%), and others (13%) are the most important. After the use phase, around 53% of the waste material is incinerated with energy recovery, one third of the plastics waste flow is recycled mechanically, and roughly 11% is used for feedstock recycling. Only minor fractions of the waste flow are landfilled or reused.
We describe and evaluate the available LDPE processing technologies with accompanying analysis of a newly developed technological line for LDPE processing in the paper. Additionally, the complex process of LDPE waste management is discussed and the circular economy for LDPE films is presented.

Material and Methods

The advanced EU Member States have been using rather sophisticated systems for urban mining of plastics. These are systems of separated collection of plastic waste in the municipal sector (from residents) or from industries, offices, shopping malls and small businesses [1], [7]. We are expecting that it would be possible to recycle as much as 50 % of the produced LDPE waste in a short time.
Typically, a waste collection company transports the waste from special containers placed on the producer's site. If more plastic waste is available, the primary separation of plastic waste types, incl. LDPE, is done right at the producers' site. Separated LDPE is pressed / packaged in order to streamline transport to the final treatment site.
The input prices (purchase of LDPE from waste producers) and output prices (LDPE granulate) depend on many factors of which the main one is the global price of the crude oil and there is no direct dependence between used LDPE film and LDPE regranulate; see for example the web portal Plasticker [7-8] which shows the prices development history. The average purchase price as of today of bailed LDPE film is € 0.27/ kg. The deviation between the maximum and minimum purchase prices for this material was from +16% to – 23% compared to average value during the last 12 months. The baled LDPE film market price development for the last 60 months is shown in Table 1.

Table 1 Baled LDPE film market price development in last 60 months. Source: [9]

Bales EUR/kg	*12 Months*	*24 Months*	*36 Months*	*48 Months*	*60 Months*
Average price	0,275	0,271	0,270	0,264	0,267
Max. price	0,34	0,36	0,36	0,36	0,36
Min. price	0,23	0,21	0,21	0,14	0,14

The average price of LDPE pellets has been fluctuating around €0.86 over the last 12 months. The maximum deviation in prices was from +14% to – 18% compared to the average value during the last 12 months. LDPE granulates market price development for last 60 months shown on the Table 2. .

Table 2 LDPE granulate market price development in last 60 months. Source: [9]

Granulate EUR/kg	*12 Months*	*24 Months*	*36 Months*	*48 Months*	*60 Months*
Average price	0,863	0,832	0,844	0,850	0,852
Max. price	1,03	1,03	1,03	1,03	1,03
Min. price	0,71	0,7	0,7	0,7	0,7

All this means that the following variables are of key importance when specifying the final treatment solution of plastic sources from plastics waste management:

- The transport distance from the collection or logistic site (anthropogenic material stocks) where the plastics waste is pre-treated to the site of final processing (regranulation) for pellet production.
- The share of LDPE film types (colour, clear, contaminated films and such) because the purchase prices vary considerably.
- Capacity of the regranulation line where pellets are produced.
- Quality of the final material.

Let´s analyse these above aspects.

Choice of optimum waste collection region and logistics

As efficient transport of waste LDPE is essential, different models were prepared for transport distances as cross-border cooperation with EU countries would be possible - typically, there are better purchase prices for the LDPE waste that has been sorted and pressed.

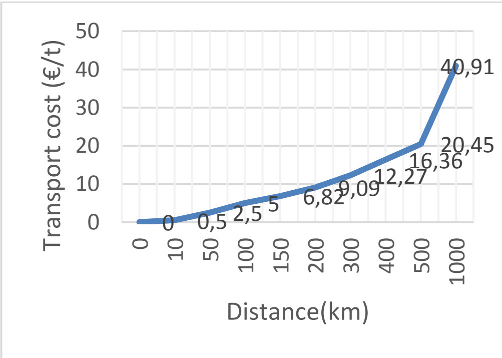

Fig. 1 Transport cost dependence 98/2 film

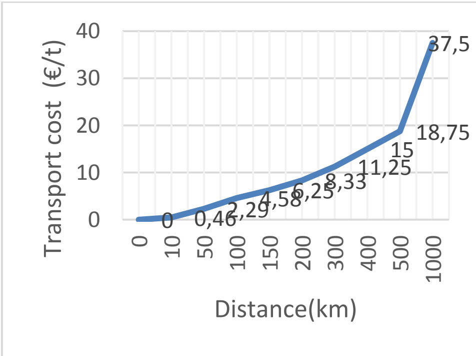

Fig. 2 Transport cost dependence agro film

Figure 1 and 2 show nonlinear increase in costs of transport to the final treatment facility. In theory the truck can transport 24 t of payload what represents 32 Euro pellets place or 90 m^3 of volume. However in reality it is estimated that no more than 22 tonnes of clean film (98/2 quality) could be transported by a single truck/trailer load. For the agricultural film due to its high mineral contamination the payload is expected to be 24 t. The average price per transport kilometre is at this time ranging between €1,1 to € 0,90 where's higher price applies to short distance and lower price applies to longer transportation distance.

One of the aspects that shall not be forgotten when designing optimum waste collection region and developing the business opportunity is the logistic of the waste. Its note very common that all waste stream is coming from one source only. Also it's not very common that only single flow of plastic waste originates at this source. The mono flow scenario may be interesting for plastics producers to process their own "In house waste". More common situation is that the waste is collected from several sources with several plastic waste flows. These sources can be spread around the industrial area, the town or the region. LDPE film originating at each source is of smaller quantity and installation of bailing facility on each of those sites may not always be the most economical solution. In some cases this situation can result in needs of creation of suitable facility to collect the plastic waste and prepare it for further transportation and processing. These logistic centres can serve as regional hubs for further handling.

These facts as well as others regions specifics puts imperative on importance of proper design of waste logistics system. Unappropriated logistic structure can send the project to "red numbers" in a short term.

Shares of the LDPE types

Key assumptions were made for modelling the optimum composition mix of input plastic materials for the regranulation line:

- The input materials do not originate from one waste supplier only. For the sake of safe business, input material shall be supplied from several suppliers.
- Plastic waste producers in the field of waste collection produce both transparent and colour films.
- In order to obtain better commercial standing, it is necessary to purchase even LDPE films that are slightly contaminated – this will be in line with requirements of most waste producers.
- It will be also possible to include new waste producers into the customer portfolio.

A new phenomenon that has recently surfaced pertains to efforts of major LDPE film producers to introduce in-house recycling. This is particularly the case with those who have large quantities of transparent films. Some other plastic film producers approaches recycling companies with request for collection recycling and supply of regranulates made from plastic wastes of their original customers. This approach can insure to the plastic manufacturer complete control of material entering the process as the material is strictly of the same composition as the originates from the same product. This brings the circular economy to its shortest ring.

Table 3 shows the figures for clean transparent waste film LDPE 92/2 and Table 4 and for the same film that is slightly contaminated.

Table 3 Model for the calculation of gross margin for packed LDPE 98/2 in different transport. Source: Authors

transport distance	*input price*	*transport cost*	*processing cost*	*process losses (4%)*	*output price*	*gross margin*	*gross margin*
km	€	€	€	€	€	€	%
0	-386	0,00	-282	-32,52	813	112,48	13,84
10	-386	-0,50	-282	-32,52	813	111,98	13,77
50	-386	-2,50	-282	-32,52	813	109,98	13,53
100	-386	-5,00	-282	-32,52	813	107,48	13,22
150	-386	-6,82	-282	-32,52	813	105,66	13,00
200	-386	-9,09	-282	-32,52	813	103,39	12,72
300	-386	-12,27	-282	-32,52	813	100,21	12,33
400	-386	-16,36	-282	-32,52	813	96,12	11,82
500	-386	-20,45	-282	-32,52	813	92,03	11,32
1000	-386	-40,91	-282	-32,52	813	71,57	8,80

Table 4 Model for the calculation of gross margin for contaminated packed LDPE in different transport distances. Source: Authors

transport distance	input price	transport cost	processing cost	process losses (30%)	output price	gross margin	gross margin
km	€	€	€	€	€	€	%
0	-200	0,00	-302	-243,9	813	67,10	8,25
10	-200	-0,46	-302	-243,9	813	66,64	8,20
50	-200	-2,29	-302	-243,9	813	64,81	7,97
100	-200	-4,58	-302	-243,9	813	62,52	7,69
150	-200	-6,25	-302	-243,9	813	60,85	7,48
200	-200	-8,33	-302	-243,9	813	58,77	7,23
300	-200	-11,25	-302	-243,9	813	55,85	6,87
400	-200	-15,00	-302	-243,9	813	52,10	6,41
500	-200	-18,75	-302	-243,9	813	48,35	5,95
1000	-200	-37,50	-302	-243,9	813	29,60	3,64

In columns of Tables 3 and 4 means: *input price* is the price at which the sorted/pressed LDPE films in packages are purchased at pre-treatment site (estimate: € 386/t for 98/2 eventually € 200/t for agricultural film); *transport cost* is the cost of transport from the pre-treatment site to the final treatment site; *processing cost* is the cost of final treatment into pellets (estimate: € 282/t for 98/2 fil eventually € 302/t for agricultural film); *output price* is the sails price after to the client (estimate: € 813/t) and *gross margin* is the gross margin from operation.

It is clear that in both cases the gross operating margin decreases with increasing transport distance. It should be, however, kept in mind that the gross margin is still more than 10% even if a slightly contaminated film is transported over 200 km distance for treatment. Considering the fluctuations in the purchase price of plastic waste and the output prices of pellets [9], the message is clear: *the network for collection and pre-treatment of waste LDPE films should be within the maximum radius of 200 km*. This should help maintain permanent and sustainable profitability of the project. The current average transport distance to recyclers in EU countries is 380 km compared to the average distance to energy recovery or landfill, which is only 30 km [4]. Additionally, the densities of recycling sites for plastic waste recovery are sparse and due to longer transport distance some of them are non-profitable.

Choice of the recycling process and technology

The most critical of all plastic recycling aspects is a right design of the process and selection of technology supplier. As waste recycling become a “premium” business topics many companies has turn to this field and offer several compositions of plastic recycling line.

The proper choice of the recycling process must address all business case aspects such as but not

limited to: input material characteristic, output quality demand, waste processing capacity, work force demand, local specifics and others. Many recycling processes have been developed recently. Some of those processes are not differing from each other very much. Some of the processes are simple and some of them are rather complicated. Each of those has its pros and contras. Generally it can be said that there is always a good choice of the process for single material flow. The extra attention and compromise must be taken in the case of demand for processing more than one material flow. In this cases the selection must we carefully balanced.
The same situation exists with technology supplier. Manufacturers of plastic recycling technologies can be easily found in all EU countries as well as in countries as China, Taiwan, Turkey and many others. As it has been proven the place of origin doesn't guarantee the expected quality. Many top end manufacturers can be found in west Europe as well as some of those providing only average quality. On the other hand some of Asians manufacturers offer proven state of the art technology similar to those made in EU for very competitive price.

Results and Discussion

Low-Density PolyEthylene recycling feasibility study

SUEZ Recycling & Recovery Czech Republic has developed a technology line for LDPE processing (production of pellets) consisting of the following units, see Fig. 3:

- The feeding system that transports material into a crusher, which is of sufficient design and capacity to remove also the crushed materials into the washing process.
- The washing process consists of three centrifugal friction washers and two sink-and-float tanks. At the end of the washing process, there is a dewatering machine with sufficient efficiency.
- The pneumatic system transports dry crushings to a storage silo where the crushed material is stored before regranulation.
- The regranulation uses an agglomerator and a unit that feeds the agglomerate to the feeding hopper of the extruder. Then, there is an extruder of sufficient capacity with continuous filtering of molten plastic. There is also a pelletizing unit.
- At the end, there is a storage silo where the pellets are stored and a big bag filling station where the pellets are filled into large bags.

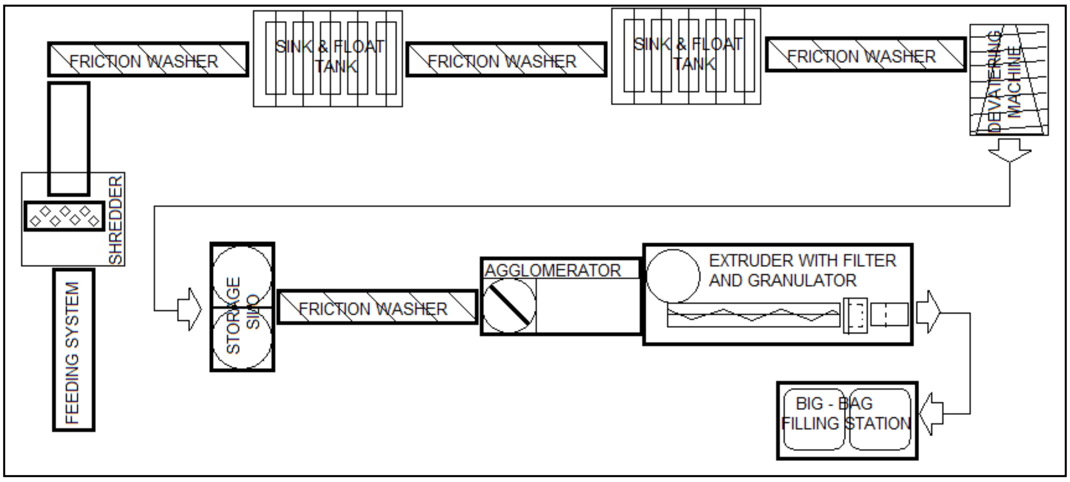

Fig. 3 Technology line – production of pellets. Source: authors

The prototype business models were prepared for basic financial plans of the lines with capacities of 3,500 and 5,000 tonnes per year. Table 3 shows the results for the same input and output values in the both lines.

Table 3 Basic financial figures for the pellet lines. Source: Authors

item\capacity	*3500 t/year*	*5000 t/year*
CAPEX (thousand CZK)	61,012	62,132
Real production (tonne/year)	3,438	4,910
Selling price (CZK/tonne)	21,787	21,787
Revenues (CZK/tonne)	74,904	106,974

Direct costs (thousand CZK)	57,522	74,725
Gross income/Gross margin (thousand CZK)	17,274	32,247
Gross income/gross margin (%)	23.1	30.1

Quality of final material

Another key factor that will influence profitability of the proposed facility for LDPE processing is the quality and long-lasting marketability of the final products. The certification will work according to the European Standard EN 15343:2007 and aims to encourage environmental friendly recycling of plastics by standardizing it, particularly focusing on the process for traceability and assessment of conformity and recycled content of the recycled plastics. It follows from the tests of input materials in existing lines that one of the key problems influencing the quality of the final product and, in turn, the price and marketability of the product, is undesirable admixtures in the final product - this is, in particular, the case with mineral contamination and pulp residues from labels. This means that the input material needs to be pre-treated; particularly, the contaminated films need to be washed thoroughly. Reliable filtering of molten plastic is also essential prior to output processing.

Two types of tests were carried out on the existing lines in order to validate the practical outcomes.

Testing the washing cycle efficiency

The washing cycle efficiency for input plastic was tested in a real full-scale industrial plant. The technology line consisted, in addition to standard components, of two sink & float tanks, three friction washers and a drying unit.

Two separate tests were performed:

- Standard treatment of the transparent film 98/2, incl. washing of crushed film.
- Treatment of the transparent film 98/2, without washing of crushed film.

It follows from laboratory analyses that if the crushed LDPE film is washed, the mineral contamination of the pellets will drop considerably. However, standard washing does not considerably reduce paper contamination in the pellets. This can be achieved by implementation of high efficiency filtration of the melted plastic in the extruder preparing pelletization.

Testing the filtration efficiency for molten plastics

The filtration efficiency was tested in three separate tests in facilities that were considerably different from each other. The results were compared and assessed in terms of operating aspects and quality of the final product.

- Test of the standard filter replaced manually.
- Test of the continuous filter, Ettlinger.
- Test of the continuous filter, FIMIC.

The first test in *standard manually replaceable filter* was carried out within the previous test on a commercial line. Standard screen filters in shifting frames for replacement were used. This is standard equipment used in recycling lines. It is a fixed steel plate with two openings, cca 300 mm in diameter. There is a frame where flat filters of corresponding size and mesh is fitted. The molten plastic flows through one filter only, while the second filter is ready for use. When the pressure of the molten plastic upstream on the filter exceeds the preset value, the filter frame moves to evacuate the used filter out of the material flow and position the new filter there.

The *continuous Ettlinger filter* was tested in a separate test comprising a standard single-screw extruder. The input material was the same as for the previous test. The material was pre-crushed in a mill and not washed. Then, the material was fed to the extruder. The working space in the filter is divided by the fixed filter into two sections. In the input section, the material is contaminated, while in the second section the material is filtered. In this case, the shape is not a plate – it is a cylinder without bottom and top parts. The cylinder surface is heavily laser perforated where the opening size is in line with the specification. In practice, filters of 100 µm mesh size are used. The cylindrical filter is attached in the holder and closed inside the working space. The molten plastic enters the external surface of the filter and penetrates through the openings into the internal part. All contaminants are caught at the external shell of the filter. The pressure of the molten plastics inside the filter is between 100 and 170 bars. The filter rotates in the working space and a blade on the filter scrapes off the contaminants settled on the filter shell. Then, a screw conveyor removes the contaminants out of the working space. The filter runs continuously without presence of operators. The service life of the filters is in range of days up to week depending on processed material.

The last equipment tested was the *continuous FIMIC filter*. The material used for the test was the same as in the previous two tests. As there is no agglomeration mill in the line, the material was prepared in an external process. In this test, the filter was installed in a double-screw extruder. FIMIC uses the same working principles as Ettlinger. The shape of FIMIC is, however, circular. The filter is divided into contaminated and clean parts. The molten plastic enters the filter and contaminants are caught on its surface. A blade rotates along the filter surface and removes the settled contaminants. The contaminants are pushed into the internal hollow part of the blade and then a small flow of molten plastic removes the contaminants into the hollow shaft of the blade. Once the pressure in the shaft exceeds the preset limit, the contaminants are released out of the filter. The filter runs continuously and does not require operators to be in attendance at all times. The service life of the filters is in range of days depending on process material.
Table 4 shows evaluation of the tests with grades 1 up to 3, where 1 is the best result and 3 is the worst result.

Table 4 Evaluation of tests with grades. Source: Authors

Test	*Procurement price*	*Operation costs*	*Requirements with respect to operation*	*Material loss*
Standard system	1	3	3	3
Ettlinger	3	1	1	1
FIMIC	2	2	2	2

In the columns of Tables 4: *Procurement price* compares the procurement/purchase price of the filtering unit; *Operation costs* compares the costs of consumables during one year operation of the filtering unit; *Requirements with respect to operation* compares the number of operators needed for reliable operation and maintenance of the filtering unit; and *Material loss* is the quantity of material excluded from the recycling process together with the contaminants.

Plastics waste management

Plastics are used in different fields, resulting in different composition of the plastic waste. When choosing a suitable commodity (or a commodity), attention should be paid to the final quality of the product (pellets or semi-products). The technology should produce top quality output products and there should be a clear link with the gross operating revenue, which should be able to absorb:

- Fluctuation in the purchase price of plastic waste and
- Fluctuation in the selling price of the final products (pellets).

It follows from data in Table 3 that the lines producing less than 3,500 tonnes per year with operation revenue around 20% are very sensitive to such fluctuations. If the overheads and expenses are estimated to be 10 %, a 10% fluctuation in prices (which is usual) can render some lines as loss-making in the period of low demand for the final product. From the long-term perspective, it is advisable to accept such risk as it is possible to arrange storage capacity and to have reasonable financial reserve for purchase of the material. Another option is to have those who supply the plastic waste to participate in the process of elimination and minimizing of the stated fluctuations.
The decisive factor for general success of the waste plastic recycling project is a suitable mix of the treated plastic films if in line with the final customer. If the line is extended on the washing side (a double washing process) and a quality filter is installed for molten plastic, the following mix can be used:

- 1/3: clean transparent films,
- 1/3: slightly contaminated transparent films,
- 1/3: slightly contaminated or clean colour films.

Other combinations are also possible – the situation in the waste collection area should be, however, considered. The objective is to optimize the chance to penetrate into the waste collection area, but one needs to keep in mind that it is only the final product of top quality that can be sold on the market.

Waste collection area

What is very important for the success of the project of plastics waste management is the waste collection area and location of the treatment facility. Analyses, summarized in Tables 1, 2 and 4, clearly show that the gross operating revenue depends on the distance from which the waste is transported. Profit decreasing linearly with increasing distance might be a key factor for modelling the location. It might be more relevant to place the line in the centre of the area than to invest more in infrastructure or purchase of land, as the latter results in depreciation of property amortized over time.

It is in particular the case of a line with rather high capacity, 5,000 tonnes per year, where increase in investments by as much as 20 % shall not drastically influence project success - returns extended by one or two years.

Conclusion

It follows from all calculations, observations, tests and models that the final solution of plastics waste management to reuse plastic waste as a material needs to relate to a certain commodity and to a particular waste collection area. The third key priority is that the solution should be part of the designed scheme, which is based on circular economy [10-11]. Considering these three facts, it is possible to create other models of urban mining of plastics for sustained profitability of the recycling process.
We can conclude that the experience gained from practice in EU Member States shows that plastic waste recycling is a risky business where fluctuations in the plastic market is dependent heavily on the price of oil and transfer of some facilities out of EU (China, Turkey, Russian) and on the demand for top quality material (only 3% of recycled material can be in a product). These risks have rendered many technologies to be loss-making. Top quality of the final product and possible placing of the final product in a warehouse is the only basic pre-condition. Close cooperation with the final processing facility (the plastic processing company) is essential if the long-term needs are to be met. And vice versa: the processing facility should be able to adjust the technological procedure and to change the product (ecodesign). Otherwise, marketability of products of top quality could be jeopardised.
Considering our prototype models above, which stem from urban mining, the following conclusion can be drawn: in order to increase the recycling of plastic waste it is necessary to integrate, promptly, the circular economy into all EU Member States. The package supporting circular economy should include the following measures:

- To increase landfill fees in countries where less than EUR 40 is paid for one tonne of waste.
- To forbid the landfilling of recyclable waste at waste landfills.
- To use EU funds for supporting the recycling and processing industry.
- To reduce taxes (particularly VAT) for products of certain quality that can be recycled from waste.
- To support research and development in recycling, reuse of waste and ecodesign.
- To support universities, specialized laboratories and research departments focused on the recycling and processing industry.
- To support certification of products with certain content of recycled waste by means of green product/eco-label/certification for products fully recyclable after end of life, or to apply a carbon tax levy.
- To support the development of local business for recycling and treatment of waste in certain regions with high unemployment with necessary logistic components (sorting lines, reloading sites, platforms for preliminary treatment of waste).

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