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Regional Replication Analysis

An assessment of the potential for additional regional plant & production lines.

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This report looks at the technology of the IEM and AM plants and determines the number of possible new plants that can be opened in Northwest Europe based on the geographical availability of feedstock and closeness to the market.

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Deliverable WPLT D2.1 Assessment of potential for additional regional plants or production line locations

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List of Abbreviations/Acronyms

AM	Additive Manufacturing
C&L	Commerce and Industry
CM	Circular Economy
HDPE	High Density Polyethylene
HWRS	Household Waste Recycling Centre
EfW	Energy from Waste
EPRS	Extended Producer Responsibility Schemes
GHG	Greenhouse Gasses
IEM	Intrusion Extrusion Moulding
Kt	kilo tonnes, 1000 tonnes
LDPE	Low Density Polyethylene
MBT	Mechanical and Biological Treatment
MRF	Material Recovery Facility
MSW	Municipal Solid Waste
Mt/a	Million Tonnes per annum
NGOs	Non-Government Organisations
NEW	Northwest Europe
PAYT	pay-as-you-throw
PET	Polyethylene Terephthalate
PMD	Plastic, Metal and Drinks cartons
PP	Polypropylene
PRF	Plastic Recovery Facilities
PTT	Pots, Tubs and Trays
RDF	Refuse Derived Fuel
SPI	Society of Plastics Industry
SUP	Single Use Plastic
t	tonnes
WfH	Waste from Households

1. Executive Summary

TRANSFORM-CE is an Interreg NW Europe funded project focused on transforming post-consumer single-use plastic waste into valuable, new products within a circular economy. To this end, two innovative recycling technologies were employed: Additive Manufacturing (AM) and Intrusion-Extrusion Moulding (IEM). The aim of this report is to identify possibilities for replication of IEM and AM plants across the four regions of Europe covered by this project. This report presents important insights gained from the TRANSFORM-CE pilot plants and identifies the key criteria necessary for replicating solutions developed for inclusion in additional regions. The business model is a circular economy model. Therefore, the plants should be small scale, near the source of materials for feedstock i.e., near consumers, and near the market i.e., the customers, to reduce transportation.

The pilot IEM plant has a 150-tonne capacity that can use low-grade thin film plastics to make durable products that can last up to 40 years and can be recycled up to ten times. The business model developed by this project was to design the plant to operate at a maximum capacity of 2000 t per year. The thin film flexible packaging feedstock is at this time incinerated to generate energy, or ends up in landfill.

The criteria used to identify future sites for IEM plants were based on the Save Plastics' Green Plastic Factory in Almere the Netherlands. Almere, with its over two hundred thousand inhabitants, is able to supply 1000 t for a plant. Extrapolating the capacity to all cities in the four regions it was found that at least 35 cities have over 400,000 inhabitants. Added to this are cities with less than 400,000 inhabitants that will grow by 2030. Further plants could be made in capital cities where many millions of people live. This implies that the number 35 is a rather conservative estimate. What is unsure is the volume or market capacity for the IEM products using recycled plastic. However, as this industry is in its infancy, and as the amount of waste plastic in the recycling system is in the millions of tonnes, there is huge potential growth for the IEM industry.

From the plastic waste data, there are millions of tonnes of plastic waste that end up in landfill or is burnt for energy. The output capacity for an AM plant was set at 100 tonnes per year. This size would be ideal for any full-size city material recovery facility that has ample capacity to fully supply the AM plant. There is data about the whole AM market and for the plastic filament market, however what is not known is the economics of the end-user or consumer side of the industry. Therefore, this report projects the number of new possible plants based on the supply of the raw materials, using a supply push economic model, to grow the end-user markets. While it is not possible to put a number on the amount of 100 t facilities that could be made in NWE, especially without end-user data, given the millions of tonnes of waste plastic that are not yet recycled each year, the potential is very large.

2. Introduction

TRANSFORM-CE is an Interreg NW Europe funded project focused on transforming post-consumer single-use plastic waste into valuable new products within a circular economy. To this end, two innovative recycling technologies were employed: Intrusion-Extrusion Moulding (IEM) and Additive Manufacturing (AM). The aim of this report is to identify possibilities for replication of IEM and AM plants across the four regions of Europe covered by this project

The project sets out to tackle post-consumer single-use plastic waste. The focus for the IEM plant was to use municipal waste streams of thin film plastics that are currently either incinerated for energy or landfilled, i.e., plastics that are not currently in the recycling system. The goal was to perfect a manufacturing process using IEM manufacturing processes to make durable products from this very low-grade plastic. This report explains the factory layout, the machinery required, and the processes the plastic go through to produce products. Currently the IEM factory is a 150 t a year pilot project, which will be upgraded to a 2000 t per annum commercial plant. It then set out the criteria used to identify where a new plant can be situated, and therefore the minimum number of plants that could be opened in the NWE.

This project was initially going to have a full-scale AM plant that manufactured filaments for 3D printers. The initial output capacity would have been 80 t over three years, or 26.6 t per year, scaling up to its capacity of 100 t by 2025. The plant was supposed to take in mixed plastics from municipal waste, sort, wash, and produce high-grade single polymer plastic granules. These granules would then be further processed to produce high-quality plastic pellets. The pellets would then be extruded to produce the filaments that can be used in 3D printers for additive manufacturing. Additional plastic waste materials for example ABS, which is less common in municipal waste streams but more well established within the AM industry, were also included for initial process trials. However, only a pilot plant was set up in the laboratory.

One of the experiments carried out was to ascertain how many times a 3D printed object could be ground up and a new product made, before the polymer chains become so short that delamination of the layers occurred, and printing a new product was impracticable. This report explains the factory layout, the machinery required, and the processes the plastic go through to produce the filaments. The plant was supposed to have been in Manchester UK and would have received its feedstock from a single MRF, that had the capacity to provide many times the capacity of the plant. It then set out the criteria used to identify where a new plant can be situated, and therefore the minimum number of plants that could be opened in the NWE.

The markets for both IEM and AM products are in their infancy, with much of the production output being for bespoke end markets rather than for the mass market. Therefore, the market size and projected growth of the end user products outputted by the IEM and AM industries is hard to quantify. This means that while a city can be identified as an appropriate place to put a plant, from the point of view of the availability of the raw input materials, however, the offtake market for the products is not full known.

There are projected compound yearly growth figures for the whole AM market, however very little information is available about plastics, and polymer types. There is data for the market value of filaments but details about end-user or the consumer market are difficult to find. This report endeavours to draw on what information there is to project on the possible number of further AM plants that could be opened in the four regions of this project.

The business model for both IEM and AM is a circular economy model; therefore, the plants should be small scale and near the source of materials and the market to reduce transportation. To grow the consumer markets for both IEM and AM, this report uses a supply push economic model. This means that since the supply is there, the business case for making a new plant will be to start small, in a place that has availability of raw material many times the capacity of the plant, and use that to grow the end-user market. Then in tandem with the increase in demand the capacity of the plant is increased to full production. For a full business model for the IEM plant see, long term deliverable 2.3 and for the AM plant see, long term deliverable 2.4.

3. The IEM industry

3.1 Location site

The core of this project is implementing circular economic business principles in the production of products made from non-recyclable waste flexible plastic films. Therefore, part of the IEM circular business model is to locate the factory such that the travelling time of both the feedstock and the products are kept to a minimum. This implies that the factory should be located as near as possible to the MRF or collection points of the plastic feedstock, as well as being near to where the target clients and installations will be. The social significance of this is that the waste is generated by consumers in the same area, town, or city that the IEM factory is making products for those same consumers. The social significance to the decision makers who procure these products is that it is reducing the carbon footprint of the area in which the waste was generated. Therefore, for a circular economic model the location and size are very important. The larger the factory the more feedstock is needed. This implies that the plastic will have to travel a longer distance to provide the high volumes of plastic required, e.g. 90,000 tons of plastic sourced each year to make 65,000 tonnes of the material hanit® (Hahn, 2022). The chosen model for the IEM plant that uses thin films is that the capacity should be capped to two thousand tonnes. By doing this many more smaller plants scattered across NWE will operate with circular economic principles.

The Save Plastics (SP) Green Plastic Factory (GPF) is co-located with Cirwinn who is the MRF that supplies the plastic feedstock. Both facilities are in the catchment area of the householders who are consuming the products that the plastic comes from. The products made by Save Plastics are at this time focused on waterways, street, and playground features that are sold to the local municipality.

3.2 The IEM plant

The plant shown here is the pilot plant that has process capacity of 150 tonnes per year. Unfortunately, currently a 2000 tonne per year plant was not built as part of this project. However, the principles of the manufacturing process and the core equipment that make up the plant do not fundamentally change when upscaling from a 150 tonne a year to 2000 tonnes. What changes is the handling equipment and the size of each machine. Set out below is the layout of the pilot plant with the operating volume of 150 t per year. Where appropriate, new processing stages and new or different equipment is discussed.

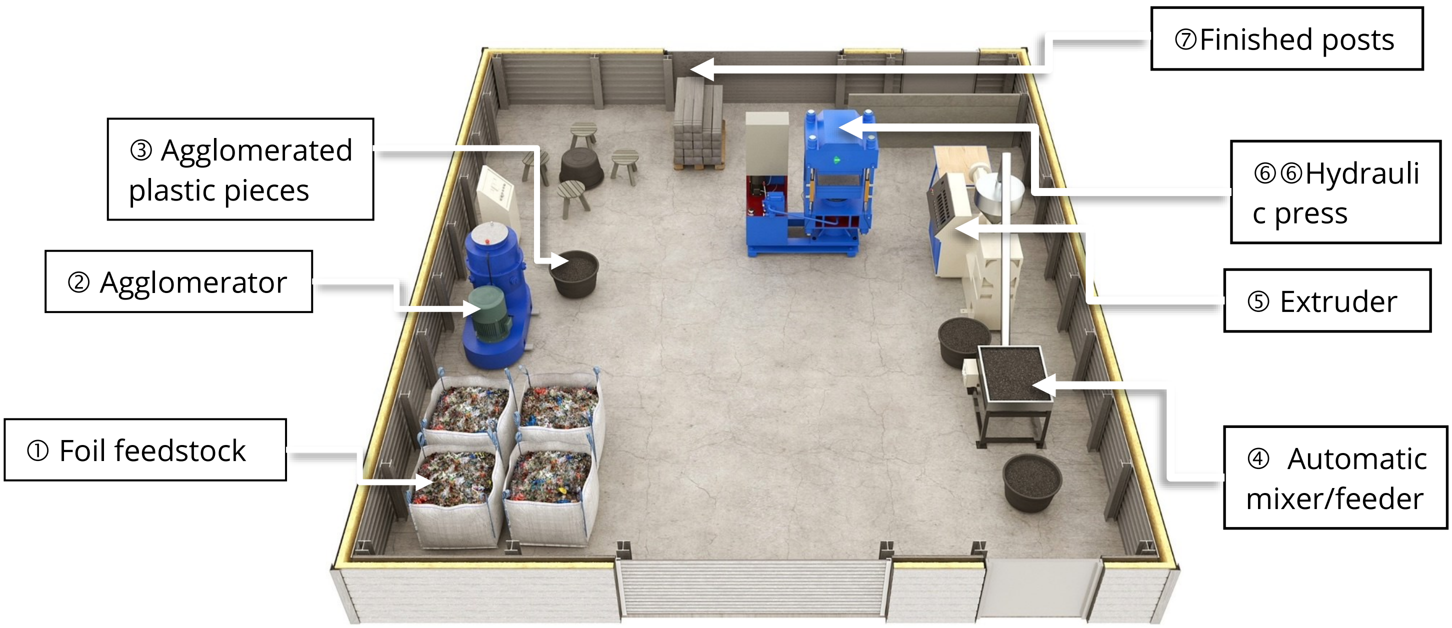

Figure 1 Layout of IEM basic single line plant

		
Figure 2 Agglomerator	Figure 3 Extruder	Figure 4 Hydraulic press

<table>
<tr>
<td>Technical Details:
1. Type: HB 150 Agglomerator
2. Volume: 150L
3. Moving knife quantity: 2 pieces
4. Fixed knife quantity: 6 pieces
5. Main Motor: type: Y180 4 power: 18.5KW
6. Rotation speed: 600rmp/m
7. Outsize: 1700 x 800 x 1500
8. Output: 80kg/h (film)
9. Weight: about 0.8ton</td>
<td>Technical Details:
1. Screw diameter 65 mm
2. The proportion of length and diameter of the screw 30:1
3. Screw rotate speed: ≤90 r min
4. Extrusion output: 30-50 Kg /h
5. Barrel heating mode: Cast Aluminium Heater
6. Heating power: 5x 4KW
7. Heating and cooling sections: 5 sections
8. Barrel cooling mode: 5 sections air cooling
9. Cooling power: 0.25 KW
10. Ac motor: 15KW
11. Machine weight: 1500kg
12. Size: 3400x1600x2760</td>
<td><table>
<tr><th>Model</th><th>XLB-600*600*1/100Ton</th></tr>
<tr><td>mold closing force</td><td>100 ton</td></tr>
<tr><td>Heating Plate size</td><td>600*600mm</td></tr>
<tr><td>Quantity of heating plate</td><td>2 pieces</td></tr>
<tr><td>Cooling plate size</td><td>600*600mm</td></tr>
<tr><td>Quantity of cooling plate</td><td>2 pieces</td></tr>
<tr><td>working layer</td><td>1</td></tr>
<tr><td>Daylight</td><td>200mm</td></tr>
<tr><td>piston diameter</td><td>300mm</td></tr>
<tr><td>Piston stroke</td><td>200mm</td></tr>
<tr><td>Quantity of piston</td><td>1set</td></tr>
<tr><td>Fluid working pressure</td><td>16 Mpa</td></tr>
<tr><td>Max fluid system pressure</td><td>20Mpa</td></tr>
<tr><td>Machine structure</td><td>4 pillar type</td></tr>
<tr><td>Heating</td><td>Electrical heating</td></tr>
<tr><td>Max temperature</td><td>300C</td></tr>
<tr><td>Control method</td><td>PLC +HMI</td></tr>
<tr><td>IR sensor</td><td>2 set</td></tr>
<tr><td>Motor</td><td>2.2 kw</td></tr>
<tr><td>Machine weight</td><td>About 3000 kg</td></tr>
</table></td>
</tr>
<tr><td></td><td></td><td></td></tr>
<tr>
<td></td>
<td>The automatic mixer/feeder is used for a few seconds to mix the feedstock and quickly fill the extruder hopper. Therefore, its power usage is deemed insignificant.</td>
<td></td>
</tr>
<tr><td>Figure 5 Automatic feeder</td><td></td><td></td></tr>
</table>

3.3 Size of the plant

The business model developed by this project was to design the plant to operate at a maximum capacity of 2000 tonnes per year. The reason for this was to operate in a circular economy that has the smallest carbon footprint as possible. The larger the plant gets, the more plastic it will need and therefore the more products it will need to produce. With a larger than 2000 tonne capacity, it is envisioned that the products and perhaps the feedstock will have to travel longer distances, creating a larger carbon footprint. If the market for IEM products exceeds the 2000 tonne yearly volume, then a new plant that is nearer the feedstock supply and the end users should be built. This means that within a large city, like the capital cities of Europe, the IEM business model will have multiple 2000 tonne capacity factories spread out across the city, rather than one huge factory. Other reasons to fix the capacity to 2000 tonnes are that the feedstock is thin films, which are only a small part of plastic waste, large weights are bulky to transport, and the products are made to order for a local market.

3.4 Pre-sorting at the MRF

The plastic is collected at kerbside in a specific PMD bag/bin and is taken by Cirwinn to their MRF where all waste PMD fractions are sorted out. This sorting action will be the same at all MRFs the only difference will be in the methodology and machines used to do the sorting. The result of the sorting is a waste fraction that consists of mixed soft/flexible plastic which is of specified content. It was found that the thin layer of aluminium in snack bags was dulling the blades during the agglomeration process and therefore if such packaging can be avoided it would speed up the agglomeration process. This pre-sort process provides an 80% to 85% plastic content for the IEM plant.

3.5 Feedstock

The feedstock for the IEM process is post-consumer single use thin film flexible packaging, that is of low-grade plastic. which is at this time only used to generate energy when it is incinerated. Included in this feedstock is food bags, for example crisp bags, that contain a thin layer of aluminium. Save Plastics' main input material are mixed plastics, which are leftovers from the recycling process that would normally not be recycled into new products. .

The feedstock should be a mixture of 70% LDPE, 20% PP and 10% other materials. Ideally it should not contain any PVC, metal or wood pieces, hard plastics, and too much sand or other debris. Small amounts of food residual are not a problem for the IEM processes. The feedstock supplied by Cirwinn consists of DKR310 (films) and DKR350 (mix plastics, mainly LDPE and PP). Both streams are largely contaminated because of residuals, laminates, food, other materials etc.

Save Plastics also offers the option for businesses to supply their own materials (e.g. films collected from packaging materials). Save Plastics will then process these materials into new products, for the business to buy back.

All of Save Plastics products are made of 100% recycled plastic. Recycled materials may come from:

- Post-Consumer Recycled (PCR) mix plastics from sorting installations, i.e., MRFs or MBTs
- Post Industrial Recycled (PIR) waste from production process or product assembly
- End-of-life (EOL) waste coming from Save Plastics' products that have reached EOL
- PCR waste from businesses

3.5.1 Storage

Depending how near the IEM factory is to the MRF there will be a need to store many tonnes of feedstock. Also, as the factory operates on circular economy principles, all prototypes, mistakes, unsaleable products, will need to be stored until they can be ground up and put back into the extruder to begin it new life as a new product. Storage is also needed for products that are made and await installation or to be sold.

3.6 Manufacturing processes

The feedstock is thin films of plastic that individually are very lightweight and not easily processed through the extruder. Therefore, the plastic needs to be chopped up, melted and formed into a heavier piece that can be easily handled and smoothly go through the extruder to be melted into a meuble clay consistent output. This process is called agglomeration.

3.6.1 Pre-sorting

Before the feedstock can be agglomerated there is a need to add a sorting process to remove as much of possible of the 15% to 20% contaminants in the feedstock. In the pilot plant the agglomerator is manually loaded, so the operator is easily able to remove any large undesirable non plastic from the waste before loading it into the agglomerator. However, there is still a percentage of contaminants. This process is slow and will not be feasible within the 2000 tonne plant. Therefore, the following equipment will be needed. The first machine is a de-baler, that will open and breakup the tightly packed bale. A conveyor belt with a magnetic separator will be used to remove ferrous metals, and then feed the feedstock into a windshifter machine that uses air separation to remove the heavy contaminants, like wood, sand, earth, nonferrous metals, and glass. The air causes the thin films to rise upwards out of the top of the machine, while to heavies will sink and be removed from the process. From the windshifter machine, the plastic can automatically be batch fed into the agglomerator or fed into large bulk bags for storage.

3.6.2 Agglomeration

The agglomerator is at this time manually loaded as it requires gradual loading, rather than a whole batch at a time. The agglomerator used in the pilot project has a capacity of 50 Kgs per hour, however for the larger plant the agglomerator will have a capacity of up to 300 Kgs per hour.

The agglomerator in the pilot plant is a large cauldron shaped machine that has two rotating knifes and 6 stationary knifes. The blades in the agglomerator act like a food blender and chop up and mix the foils. This cutting motion causes friction that produces heat which heats the plastic up to about 100^{o} C causing the plastic foils to shrink, plasticise and small pieces clump together. After a few minutes, cold water is sprayed on the hot plastic to stop the batch forming a single large clump, which would be unusable for extrusion. The amount of water is just enough to quickly cool the plastic and evaporates leaving no wastewater problem. The output is irregular shaped very small pieces of mixed plastics. This output is put into large bulk bags for storage before later use in the extruder.

It was found that the blades ware out quicker when there was aluminium coated plastics in the feedstock. Without any aluminium coated foils, the blads needed sharpening once a month, with the aluminium foils the blades needed sharpening every few days (three days was found to be a good length of time). It was found that with the aluminium the agglomeration took 3% longer. While it may seem insignificant, these 3% adds up over a yearly business cycle for energy and manhours used.

To keep downtime to a minimum the company holds three sets of blads, one is in use, the second is sharpened and ready to be placed in the machine when the dull blades are swapped out and the third is a built-in redundancy for emergency use or can be used in rotation with the other two. By doing this the downtime is minimised to the to the time it takes to swap the blades. The sharpening is carried out in parallel to the use of the agglomerator.

3.6.3 Additives

If the plastic product will be used in direct sunlight, then a UV resistant additive is mixed in. If the plastic will be used to make a house, it will need to be fireproofed and/or flame retardant, then additives are put into the mixed plastic. If the product needs extra strength, then fibres are added to the mix, these could be glass, textile or other fibres. At this stage a colour can also be added. Currently all these additives can be added to the mixer (Figure 5 Automatic feeder above) before being loaded into the extruder. In the larger 2000 tonne plant the extruder will have the capabilities to add the additives during the extrusion process.

3.6.4 Extrusion – Intrusion

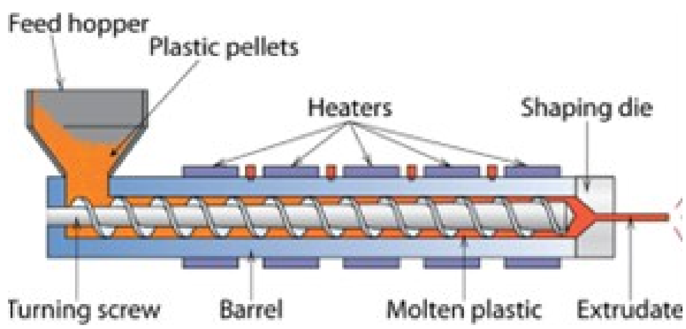

Figure 6 Schematic of an extruder

In the pilot plant the plastic is put into the extrusion hopper, and is heated up. The plastic comes out with the constancy of a clay which is weighed off and put into a mould. The mould is then pressed under pressure to form the product. If the mould is connected to the extruder the plastic will be forced directly into the mould under pressure, this is the intrusion processes. When the mould is full, it is removed from the extruder and left to cool off, (sometimes up to 4 hours), after which the product can be taken out of the mould. A second mould can be connected to the extruder as soon as the first one is removed.

The extruder currently used in a single screw extruder and in the 2000 tonne plant there will be a much larger double screw extruder. This type of extruder has the advantage of mixing the plastic much better.

The processes operating in the pilot plant are labour intensive and time consuming. Therefore, for a 2000 tonne per year plant the extrusion and intrusion processes are automated. Save Plastics have designed their own propriety automation system that has a mechanism that will have a set of moulds that can be attach to the extruder. Each gets filled with the plastic, is detached from the extruder and another mould is attached to extrude the next product.

3.6.5 The hydraulic press and the moulds

A mould in the hydraulic press, Figure 4 Hydraulic press is filled with the soft plastic and is pressed with 25-100 tonnes of pressure. After five minutes the process is complete and all that is needed is for the piece to be left to cool down. If the piece is taken out of the mould too early, when it is too warm, warping will occur. The products made at Save Plastics pilot plant using intrusion moulding, are usually large and require many hours to cool down in the mould. Therefore, to allow for full daily production many moulds are needed, as the production process does not need to wait for an empty mould.

3.7 Enhancements to the process within the 2000 tonne plant

In the future the manufacturing process with be enhanced by introducing new machines and processes that are not in the pilot plant.

3.7.1 A shredder

The IEM production process will generate waste. Some will be during the research and development of new products and others will be because of mistakes or unwanted products. As this is a circular economy production process, there is a need to input this waste back into the production process. Therefore, there is a need for a grinder to grind up waste materials into small pieces that can be put directly into the extruder. As the granulates are heavy compared to the original feedstock, they will not need to go back into the agglomerator but can go directly into the extruder.

3.7.2 Cooling down the moulds

In the pilot plant, the time it takes for some large items to cool down in the mould, is up to a few hours. This ties up the mould, which means it can't be used again until it is freed up. This is one of the disadvantages with the piolet project. Therefore, in the 2000 t plant, a propriety automation system will include a closed loop heat exchange mechanism that will cool the mould so that by the time it can be removed from the mould it has cooled down enough not to warp. There will not be a stand-alone hydraulic press, but the propriety automation system will include a press. With automation, the output capacity of the factory will be vastly increased.

3.7.3 Mechanism to dry the plastic

At this time the pieces of plastic come out of the agglomerator are moist. While this has no significant effect on the processing of the plastic, if the agglomerate was dry, this would improve the performance of the machines and they don't wear out as fast. Therefore, in the design for the 2000 t plant degasification technology will be used to remove the steam and thus moisture during the processing of the plastic.

3.7.4 Human power and automation

At this time the scale of operations at Save Plastics is small compared to its final size when it will have the capacity of 2000 t per annum. Therefore, the visual quality control carried out on the waste plastic is carried out when the plastic is manually loaded into the agglomerator. This visual inspection is to find and manually remove, big pieces of metal or wood. In the future, after the de-bale there will be an air separation machine (a windshifter) that will separate the very light thin plastic films from all other heaver materials. This removes the manual inspection and sorting that is carried out before agglomeration.

3.7.5 Air purification system

There may be a need for air purification or fume extraction system depending on the size of the room, the location of the plant, and if there is natural ventilation.

3.8 Types of IEM products produced

There are two approaches to the IEM business. The first which is carried out by companies like Hahn (2022), Ecoo (Ecoo, 2022) and Govaplast (Govaplast, 2022), who have factories that process huge amounts of waste plastic, hold large inventories, and in Hahn's case sell over 2000 products. The feedstock they use is predominantly the hard types of plastic like the HDPET, LDPET and PP. From their websites it looks like they make standardised products, but are able to make bespoke products. However, such companies are predominantly geared to mass production and therefore do not focus on small production runs and bespoke designs. Furthermore, their products lifecycle is not geared to be local, something that is not in accordance with circular economy principles.

The design of the IEM plant for the TRANSFORM-CE project focus on the use of thin film packaging waste rather than hard plastics. This reduces the volume of feedstock available from municipal waste. The IEM business takes a waste product that currently have a negative value, as it costs to dispose of it, and add the maximum value to the product. It focuses on making niche products made to order. The goal is to use the plastic as part of a larger or expensive product rather than make generic cheap components that have multiple uses. By adding value to the products produced, profit can be maximised. For example, if generic fence posts are made, they are only sold at a low price. However, if added to this are fence panels, then what is being sold is a fence rather than the individual items. Similarly, if the plastic is made into the components that when put together becomes a bungalow, then the value of the plastic is being maximised, as now the plastic is part of a house and not just as cheaper paving brinks for a new pathway. The plastic is now sold as a house in the tens or hundreds of thousands of Euros, or Pound, depending on size and location.

Example products

- Indoor furniture
- Outdoor/street furniture
- Playgrounds
- Building materials
- Public space infrastructure (poles, bollards, lamp posts, fences, boardwalks etc.)
- Canal Jetties, retaining infrastructure, and bridges (the Netherlands)
- Living spaces, bungalow, and sheds

Products are designed in such a way that they are simple, and parts can be easily replaced. Because of the low purity of materials, it is not possible to work with extreme accuracy. Experience is needed for designing the moulds. For example, thickness of the product, wall thickness and warping of products need to be taken into account. The moulds for made for Save Plastics are built with layers of sheet metal. Each layer is laser cut, which makes the mould about ten times cheaper than those used in industrial settings. Moulds can also be designed to allow adjustments for variable sizes, e.g. a mould with an interchangeable core to allow for different diameters.

Recycled plastic products are more expensive, but also more durable than for example a featheredge wood fence, with a potential lifespan up to 50 years of continual usage.

3.9 The circular economy at Save Plastics

Save Plastics, and therefore by extrapolation all manufacturers using their business model, embed circular economy principles at all stages of their production cycle.

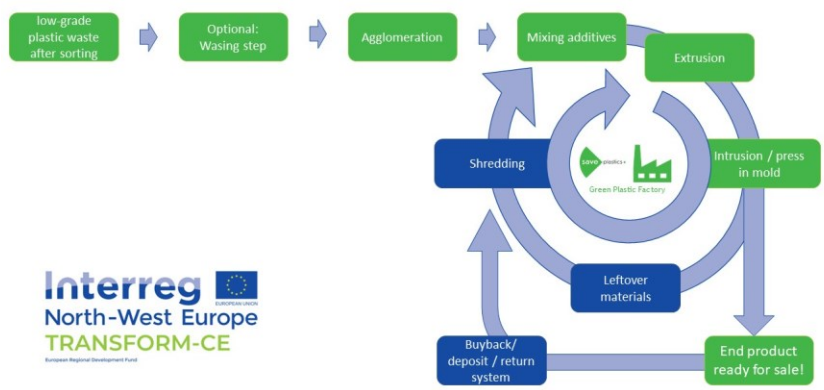

Figure 7 the circular economy model for the Save Plastics Green Plastic Factory

3.9.1 Products are design for circularity

Design for circularity by Save Plastics manifests itself in three ways: *design for disassembly, design for recycling* and *design for durability and performance*.

Design for disassembly

Because of the large size, products will always have to be disassembled before being recycled. Products are mechanically connected by means of screws. Broken parts can therefore be easily removed and replaced.

Design for recycling

The products and used materials can be recycled up to ten times. Some products are made of a combination of materials. For their combi-pole made of wood (used because of costs) and plastic, a machine is needed to pull off the top part that is made of plastic. For some jetties and bridges, steel reinforced bottom beams are used for strength and stability. This means that only about 70% of the plastic can be cut out after use for reuse in a new product.

Design for durability and performance

Products from Save Plastics last for up to 50 years, which is longer than (wooden) alternatives. They will not rot or splinter, can withstand rain and can be made UV resistant. They also don’t need painting or wood preservers to elongate their useful lifespan.

3.9.2 Circularity of waste at Save Plastics

Material recovery may happen at several places along the value chain: during manufacturing, during product cutting or just before installation at the customers' site. Most important is that these material and sawing losses do not end up in nature. During production, there may be industrial cutting waste, but there may also be product failures caused by the mould not filling properly or first pieces when connecting the mould. When products are cut to size, all waste (e.g., sawing losses) is saved, recycled and reused in new products. Cutting of products happens indoors at Save Plastics, so materials can be captured in a controllable way. Material recovery may also take place at the customers if they decide to cut products again before installing them. Sawing losses will then include pieces of 5-20 cm and are brought back to Save Plastics in big bags or on pallets.

Save Plastics offers the option for customers to return products at end-of-life or end-of-use. The customer remains responsible for product disposal, which also means they have to pay for transportation. Save Plastics is looking into the possibility to implement a 1% to 2% removal fee upon purchase of products, but this is often the first thing contractors want to eliminate. Introducing a deposit is an option, but this will have to be worked out in the future.

Together with the customer, Save Plastics looks for options to give new purpose to products that have reached end-of-use. An example of refurbished products includes those that are no longer needed by the customer. For example grass tiles, which are hollow frames that are installed at the edge of roads or in places where vehicles go. (They stop degradation of the earth from the traffic.) These products were bought back, cleaned and later resold to another municipality.

3.9.3 Further opportunities for circularity

Although Save Plastics has been using recycled materials as input for products for over 30 years, there are still some opportunities to further enhance circularity of Save Plastics' products. The company also realises this and is exploring options for products at end-of-use.

Access

A big opportunity to boost sales is envisaged if products are not directly sold but are leased out and paid for by monthly or quarterly subscription. This means *access* to a product is provided, and Save Plastics remains responsible for product maintenance, repair and collecting the products at end-of-life. Municipalities often have a fixed budget. When products are paid for through a monthly subscription fee, this helps the customers cash flow situation. However, as Save Plastics will only receive monthly payments, it will be necessary to be able to finance the costs of production and the cash flow of its own business. This business model is high on the company's agenda, and they are exploring opportunities to implement this.

Repair and maintenance

Save Plastics' products last approximately 50 years and may be recycled up to ten times. However, it may sometimes be the case that a certain part gets damaged or brakes. Save Plastics offers single parts as a replacement, but options for this strategy could be further explored. For example, if the customer is paying a subscription for the product, replacement parts may be free, or if chargeable the replacement fee could be waivered.

Refurbish
Save Plastics products can be returned to the company at end-of-life to be recycled. However, some of the products are still (partly) usable and can be given a new purpose. Hence, it will be valuable to explore options for products at end-of-use. This may for example include options to give products a new purpose. Together with the customer, Save Plastics looks for new application options. An example of refurbished products includes grass tiles which were no longer needed by the customer because of road widening. Such opportunities could be further explored, and Save Plastics is actively working on this together with its customers.

Local circular economy
Next to circular strategies, opportunities are also seen to further enhance a local circular economy. To reach this goal, the Save Plastics pilot plant has been set up to process local waste for local applications. This will save transportation operations, costs and reduce CO_2-emmissions. Save Plastics is therefore actively looking into more opportunities to work on a local level and stimulate the implementation of a local circular economy. A selling point is the making of products from local waste reducing local environmental damage.

3.10 Volumes of plastic available for IEM

The availability of waste plastic for future use by both AM and IEM has been documented in the first Long Term report delivered through this project, see LT 1.1 report for all the details. Although the Save Plastics have concentrated on thin films that are currently not recycled, their IEM plant can take in PET, PP, HDPE, and LDPE, if it is granulated and can be inputted directly to the extruder. Therefore, any IEM plant can take in most plastics. Thus, the total aggregated amounts of waste plastic across all four regions which was approximately 9.5 Mt per year Table 1: Total plastics in waste streams (based on dates in citations) are potential inputs to the IEM plant.

Table 1: Total plastics in waste streams

	national plastic waste streams [kt/a]				
Waste stream	**Germany**	**Netherlands**	**Belgium**	**UK**	**total**
residual	906	357	201	1.705	3.170
commercial residual	247			2.314	2.561
packaging	2.446	185	119		2.749
packaging commercial	349		117		466
deposit return	467	42			509
total	**4.416**	**584**	**437**	**4.019**	**9.455**

Germany 2018 (Dr. Dornbusch et al., 2020), Netherlands, composition is three years average over 2018 - 2020 (Rijkswaterstaat, 2021), residual Belgium (RDC Environment SA, 2019) Belgium, packaging (Valipac, 2020), Residential England 2017 (WRAP, 2019b) Commercial England 2017(WRAP, 2019a)

In the Netherlands 40% of the packaging waste is thin films DKR310 and DKR350, (email from P. Mul). Therefore, at the time of writing this report, there is potential for up to 125 kt of DKR310 and DKR350 available per year for IEM production.

For the UK in 2019 there was approximately 415 kt of plastic films from non-consumer plastic packaging placed on the market (RECOUP, 2020, p. 33) only a small amount of which is recycled. Therefore, the rest will be potentially available for any future IEM facility. The exact amounts of feedstock available in the other two regions is not known. However, given the total amount of plastics ending up in the residual waste stream, it is estimated that there are more than one million tonnes of packaging plastic available per annum that could be use in the IEM industry.

From Table 1, of the 4.4 Mt of plastic waste that was identified in Germany, more than 2.1 Mt of plastic was not intended for recycling and thus is available as a potential input to the IEM industry. For the Netherlands out of the 600 kt identified, 285 kt were not intended for recycling and is also potentially available. Similarly for Belgium, 300 kt was available out of 465 kt and for the UK, 3.2 Mt was available out of 6.3 Mt, see Table 2: Plastic waste available for pilot plants below.

Table 2: Plastic waste available for pilot plants

national plastic waste available for pilot plants [kt/a]					
Waste stream	**Germany**	**Netherlands**	**Belgium**	**England**	**total**
residual	906	197	201	1.356	2.660
commercial residual	247			1.930	2.177
packaging	964	89	26		1.079
packaging commercial	unknown		70		70
deposit return	-	-			-
total	**2.117**	**285**	**298**	**3.286**	**5.986**

The PET collected from the bottles in Germany and the Netherlands is high quality plastic that is recycled, however, what is not known is what happens to the labels, that are usually PP (type 5) and the lids which can be either HDPE (type 2) or LDPE (type 4). Therefore, there is a potential that this waste, which should be highly uncontaminated, can be a source of feedstock for the IEM industry.

It is not known how much of all this currently not recycled plastic is thin film and how much of it is more rigid plastic, which is currently not being used by Save Plastics. The use of hard plastics in IEM can be technically possible with the use of conventional shredders that can reduce the plastic to very tiny pieces. This would imply that with preparation, all the 5.9 Mt of waste plastic could be available for IEM. This volume implies 2,950 two thousand tonne factories across the four partner countries. In reality, much of the plastic will be used elsewhere including keeping the EfW facilities running. Therefore, it is not possible to identify a definitive number for the amount of potential 2000 t facilities.

All the statistics in this section are taken from municipal waste data, however, there is also the waste collected by private commercial waste management companies. This waste adds to the total future amount of waste plastics that will be available for both AM and IEM.

3.11 Potential for additional plants in partner countries

Save Plastics' pilot plant the Green Plastic Factory is situated outside the city of Almere in the Netherlands, which has about 220k inhabitants. In Almere they collect about 25 kgs per inhabitant per year in the PMD collection. Of this, 80% or 20 Kgs is all types of plastic. Using the statistic of 220,000 inhabitants, then the amount of plastic waste generated per year is approximately 4,000 t. Of the plastic collected about 25% in low quality plastic foils. This equates to 1,000 t of low-grade plastic that will be available for the IEM plant. Therefore, on average there needs to be about 440,000 inhabitants in a conurbation to provide 2000 tonnes to an IEM factory. Or at 5 kg of low-grade plastic per year, any geographical area that has approximately 440,000 inhabitants, could supply a 2000 t capacity IEM plant. This includes losses of about 10% in the manufacturing process.

From statistics gathered and presented in Appendix 1 below, the UK has 15 such sized cities (The Geographist, 2022), Germany has 15 (citymayors.com, 2022), The Netherlands have 3 (worldpopulationreview.com, 2022), and Belgium has 2 (geoba.se, 2022). Therefore, the minimum amounts of possible new IEM plants with a 2000 t per annum capacity, is 35. There are further cities that have over 350,000 inhabitants and as urbanisation is destined to grow (Watson, 1993; Zhang, 2016) they will be able to open their own plastic factory. This number 35 is a conservative estimate of the capacity for the IEM industry to grow. However, it does not take into consideration cities with inhabitants in multiples of 400,000, which will increase this estimate by approximately 23 plants. It also does not take into consideration towns which individually do not have enough waste foils to feed an IEM plant, but being in close proximity to each other could with a short travel distance supply a 2000 t per annum plant. On the other side of the equation, the number 35 does not take into consideration factories within the four partner countries that are already opened. If 35 new 2000 tonne capacity plants were to open, that would divert from EfW and landfill, 70,000 tonnes of waste plastic films per annum. This number is a small fraction of the 6 Mt of unrecycled waste plastic in these four countries.

3.12 Potential for additional plants in other countries around the world

According to Citymayors Statistics (2017), there are over 300 cities worldwide that have populations of over 2.2 million people when the metropolitan or greater city inhabitants are included. For example, in 2017 London had 8.67 million inhabitants, but the metropolitan area of London had 13.88 million inhabitants. Similarly, Berlin had 3.6 million inhabitants which almost double to 6 million when the greater metropolitan area is taken into consideration. From their statistics of cities within geographical Europe, there are over 131 cities that have 400k inhabitants (CityMayors Statistics, 2022). This means that the potential for the IEM industry is enormous.

While the supply of thin film plastic can be found in all these cities, what is the market capacity for the products outputted by the IEM industry?

3.13 The IEM market analysed

Millions of tonnes of plastic products are made each year from virgin plastic, some of which could be made with recycled plastic. The IEM industry is a relative new industry to use recycled plastic. Production of products made from recycled waste plastic through the IEM manufacturing method has been in continual operation for more than forty years. However, both the production tonnage and the size of the market is very small, compared to the amount of waste plastic that is currently not recycled and the size of the market that these products could be substituted for. Given the list of possible products that can be made, it is surprising that the industry is not as large as it should be.

Some of the problems with this industry is the reluctance of municipalities and consumers to embrace these products. In some instances, there is a worry about ecological damage, although there is a good track record going back many years that these products operate within safe limits. There is also the higher cost for an IEM product than for a wooden one. For example, a wooden feather edge garden fence panel will be much cheaper than a plastic one, hence the reluctance to buy the plastic one. However, when the life cycle of the plastic fence is taken into consideration, including the cost and maintenance, plastic workouts cheaper and need less maintenance than a wooden fence. A wooden fence may need to be painted with a preserver every five or so years and will only last perhaps 20 years. Therefore, for a 50-year lifetime of the plastic fence, that is equivalent to the cost of two and a half fences, without the maintenance. A further advantage to IEM products is that the material used to make them, i.e., the plastic, can be used again many times, while the wooden fence decays and the wood is finally consumed.

The whole IEM business is niche and has a few large businesses across Europe. Therefore, statistics about the market is not available. However, given the amount of wooden, and metal products that could be substituted with solid plastic using IEM technology, there is huge possibilities for expansion of the IEM industry.

Many municipalities and states have a growing problem of what to do with their waste plastic. IEM offers a circular economy model for the local municipality to be involved in producing large scale products made from local waste that can be used by local consumers. Examples are street furniture and playground objects.

The expansion of the IEM market will depend on support from public authorities and consumers creating the demand pull for the products and ingenuity on the part of the IEM manufacturers creating the supply push.

4. The AM industry

In general, the additive manufacturing (AM) industry incorporates the manufacture of products using many types of materials. These include metals, plastics and bio-materials. This project focuses on the use of different plastics used in the AM industry. Metals are the largest part in terms of monetary value, however, the most prolific with the most users are those that print using plastics.

The TRANSFORM-CE project was originally going to include a full-scale plant that would make filaments from municipal single use plastic waste. The three-stage process would have been as follows, firstly to take single use household plastic waste, collect, sort, clean and shred the plastic, and produce single polymer clean plastic flakes. Secondly, these flakes would then have been melted and extruded to produce pellets for use in making filaments. These pellets must be ,ore than 95% pure, therefore the need for the input feedstock to be of very high quality. The third stage would have been to add the required additives and produce 1 kg spools of single polymer filaments to be used in AM printing. The production facility would have had an initial operating output of 80 tonnes over three years with the ability to scale up to 100 tonnes per year.

The full-scale plant was never built, but a desk top laboratory installed pilot production facility was set up. The feedstock was bought in as pure single polymer pellets, which were extruded to make filaments. The pilot plant was then used to recycle the filaments to identify how many times the plastic could be recycled before it lost its mechanical properties and could not be used in desktop 3D printing. This report is about how the 3D manufacturing facility could be rolled out in different places in NWE. Therefore, it will look at the original plans to determine the processes need and then discuss possible proliferation of news plants.

4.1 Site location for plant

The full-scale plant would have been in Manchester UK, where the tonnage needed to fully supply the plant with up to a 100 tonnes per year would have been ample. As this is a circular economy project, the site chosen for the production of the pellets and the filament should be situated as near as possible to the collection of the plastics, usually a MRF, in order to reduce transportation to a minimum.

4.2 Plant layout

The layout of the proposed plant was set out in a floor plan drawing that is reproduced here in Figure 8 Commercial sized granulator and mixer and Figure 9 layout of a commercial filament production facility below. The filament production process begins with stage two, which is the pelletisation of the clean plastic flacks received in from the MRF.

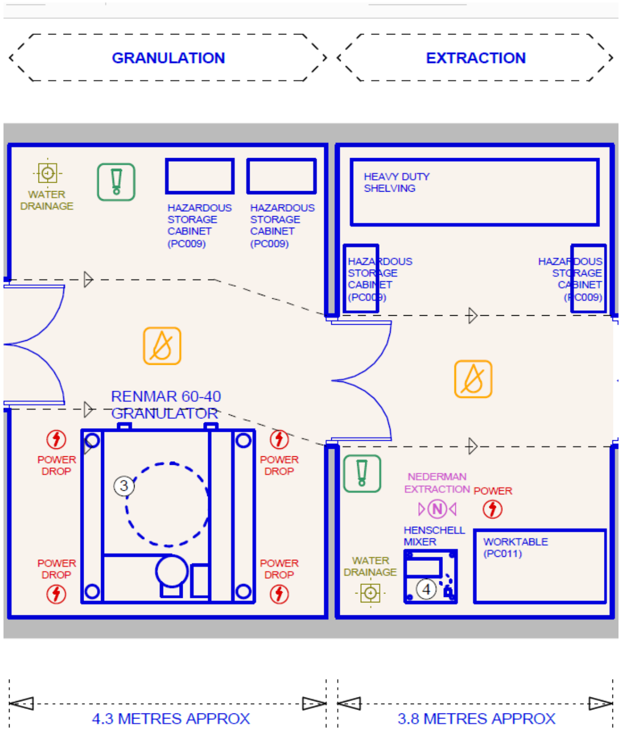

Figure 8 Commercial sized granulator and mixer

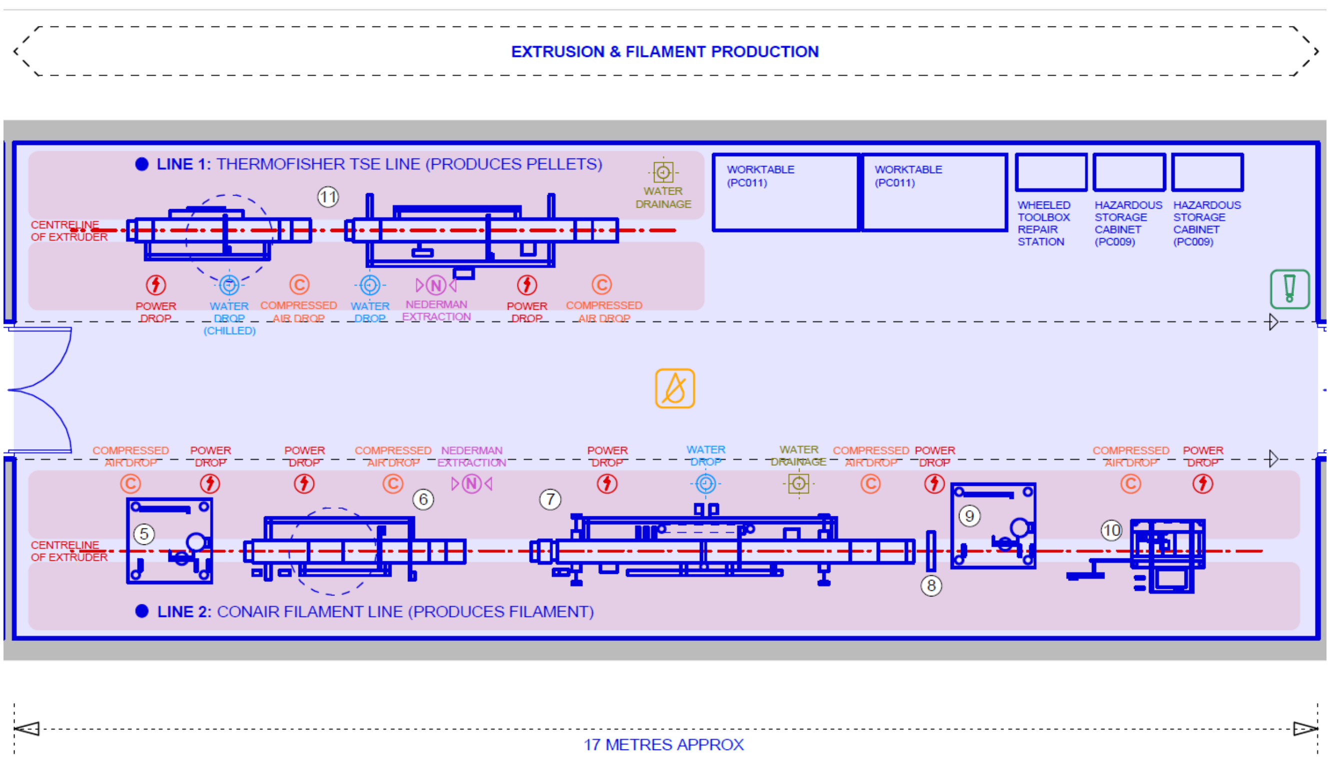

Figure 9 layout of a commercial filament production facility

4.2.1 Granulation of the plastic flacks and mixing the additives

The plastic chips should be almost 100% free of any contaminants and be almost moisture free. However it may need some visual inspection to remove any impurities found. A Renmar 60-40 granulator is used to grind the plastic to a maximum size of approximately 3 mm.

Figure 10 Renmar 60-40 granulator #3 in Figure 8 Commercial sized granulator and mixer

The Henschell mixer is used to mix the required additives into the plastic. This is carried out before the plastic is inputted to the extruder.

Figure 11 Henschell Mixer #4 in Figure 8 Commercial sized granulator and mixer

4.2.2 The manufacturing process of pellets

This process uses the Thermo Fisher TSE24 twin-screw extruder equipment which has a output of 50 kg/h. At the initial output of 26.6 tonnes per year, the production was predicted to be 26,666 1 kg spools of filament. At the rate of 50 kgs per hour this would take 534 hours over one year. When the production is ramped up to 100 tonnes the production would be 100,000 I kg spools, this will take 2000 hours to produce over a single year. It is not known if this machine is able to produce this amount of output on a yearly basis.

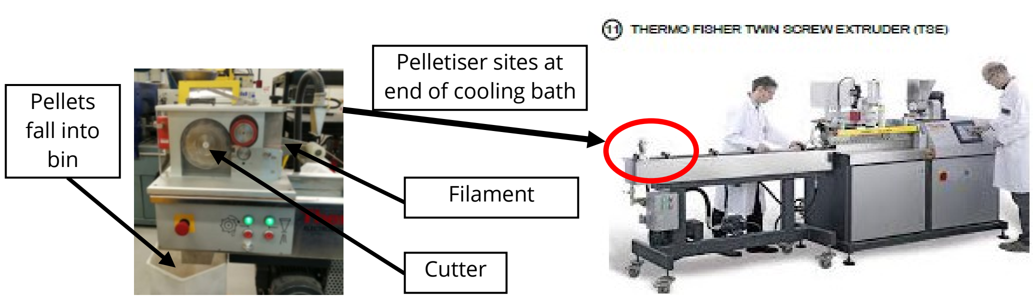

Figure 12 Thermo Fisher twin screw extruder and pelletiser

The pelletiser in mounted on the end of the cooling bath and has a cutting wheel that produces the pellets. This is the configuration at the moment in the lab. However, in a 100 tonne a year plant the pelletiser will be of a larger size that can produce 100 kg per hour. Its extruder head will produce up to 10 filaments that feed into a large standalone pelletiser Figure 13 The extruder head, extruding 10 filaments that will be cut into pellets.. For example, the ASG SHJ50 model, (ASG, 2023).

Figure 13 The extruder head, extruding 10 filaments that will be cut into pellets.

4.2.3 Drying the pellets

This project specified six pieces of equipment from Conair that make up the filament extrusion and real production processes. The first piece of equipment is the pellet drier.

The pellets are of approximate 5mm in diameter while the filaments are produced with less than 1 mm in diameter. In order to successfully extrude at below 1 mm, the plastic must be very dry, or have no water moisture. The reason for this is that at 300 plus Celsius the water moisture vaporises and forms bubbles within the plastic. At the extrusion head busting bubbles cause breaks in the filament and deformities in the thickness of the extruded filaments. It was also found that moisture in the filament is one of the causes of poor adhesion of the printed layers, otherwise known as 'poor lamination'. Poor lamination leads to the printed item splitting or breaking. Therefore, a drier is specified to reduce the moisture of the pellets before they are put into the extruder. At the MMU pilot plant the pellets are heated to 60ºC for a few hours to remove all the moisture.

The DH Series Insulated Hoppers from Conair offer large volume air drying for the plastic pellets.

Figure 14 Conair DH Series Insulated Hopper

4.2.4 Filament production

The filament production line consists of Conair products (Conairgroup, 2023). It consists of a filament extruder, water cooling bath, a laser measuring device to check the diameter of the filament, a puller machine to move the filament along, and a spooler/coiler machine that winds the filament onto the spool.

Figure 15 Conair filament extrusion line

4.2.5 Air quality – Fumes extractors

A Nederman extraction unit is used in three places to extract fumes that are given off from hot plastic. The first is used above the mixer, and the other two are used above the two extruders. It is assumed that the extraction unit is centralised with extraction arms coming down from the roof.

4.2.6 Printing products

There are many uses for 3D printing that offer practical, economical and time saving advantages over other traditional manufacturing methods. These are.

- On-demand manufacture
- Jigs & fixtures
- Minimal set-up costs (no tooling)
- Inhouse production or as third-party service
- Rapid prototyping, better meet customer requirements
- Reduces machine and customer downtime
- Repair single components
- Easley produce spare parts on demand
- Customised / small batch products
- Complex structures
- Unique geometries not possible through other means
- Light weighting with honeycomb type internal structures
- Less plastic used with hollow/ honeycomb structure
- Generative design
- Bespoke filaments
- Recyclable products

This project has worked with 3D printers at Print City (MMU, 2022), to produce many prototypes and one-off items that showcase the use of the different plastics. The plastics are also used to repair broken items that are being saved from the dustbin, this is part of the Interreg NWE project called ShaRepair (Interreg-NWE, 2022) operating in Manchester UK through Print City (printcity, 2022). The printers used are shown in Figure 16 two types of desk top 3D printers below. The size of products are small and the types of plastic used are either one or two depending on how many print heads have been installed. It I possible to print with two different colours if there is two printheads. Users of additive manufacturing are SMEs, large businesses, schools and education providers, individuals, and hobbyists.

Figure 16 two types of desk top 3D printers

4.2.7 AM end products

For the above printers the plastic filament must be of very pure single polymer and the nozzle size is usually less than 2 mm. However, there are larger format printers that use a robotic arm to print with a width of up to 30 mm and create pieces of up to 12 meters long. The robot arm moves on rails as it prints the product. Figure 17 3D printing technology using a large robotic shows a lounge sofa being printed by a robotic arm, (10-xl, 2022).

Figure 17 3D printing technology using a large robotic arm to print a sofa (10-xl, 2022)

The advantage of printing with a print head of up to 30mm is that the purity of the plastic does not need to be at the level of ordinary 3D printing. Therefore, all the waste from ordinary printing can be recycled in a circular manor by reusing it in a large format printing like that used by 10-XL. As these are very large objects reinforcing fibres are used to strengthen the product. In such a printer, the clean dry plastic flakes are put into a hopper fed extruder, which feeds the molten plastic directly to the print head. This has the advantage that no filament is need. The less the plastic is heated the more times it can be reused before it needs to be mixed with virgin plastic or depolymerised using chemical recycling. This is due to the shortening of the polymer chains caused by the heating up of the plastic. Short polymer chains make it difficult to extrude the filament as breakages occur.

While the prevalence at the moment is to print one-off items, in the future 3D printing will be used to produce runs of up to 1000 products (Ernst & Young 2019).

4.2.8 Auxiliaries

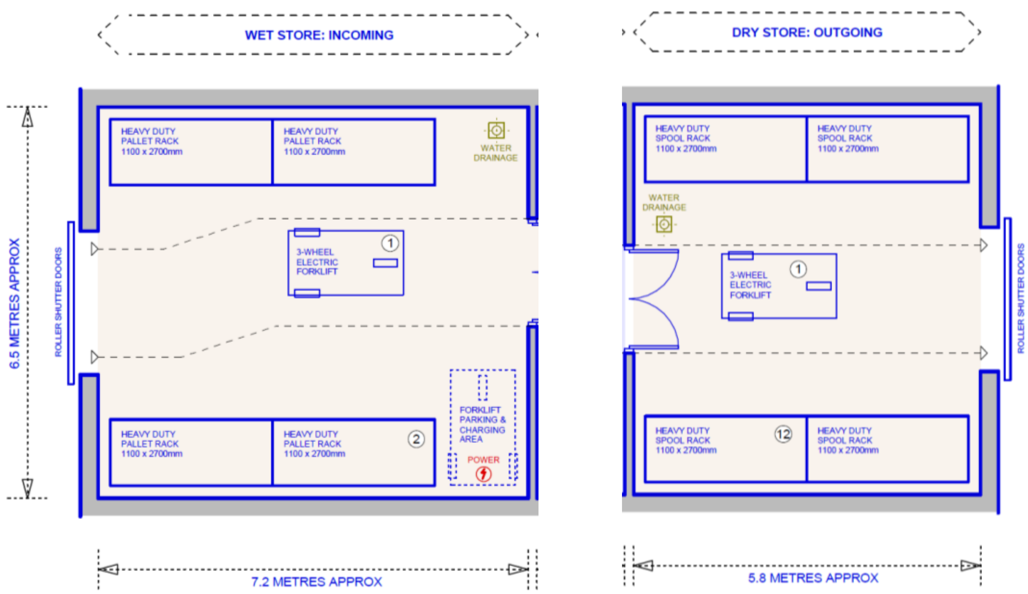

Figure 18 the auxiliary storage areas

Capital investment is needed for pallet shelving to store the inward bound wet/moist plastic flakes and for the finished roles of filament. Also required is a vacuum sealing machine to stop the filament absorbing moisture from the air as it waits to be used. A forklift is needed to move raw materials and products around the plant.

4.3 Volumes of plastic available for AM

While it has been shown that the volume of plastics across the regions within this project is approximately 6 Mt Table 2: Plastic waste available for pilot plants, this is for all types of polymers. What is not known is the available volume of any one polymer type. Furthermore, as the most prevalent 95% of plastic used in the UK is PLA (Fillamentive, 2021) it Is not known the distribution of this polymer across NWE.

4.4 Output capacity

The production facility had an initial operating output of 80 tonnes over three years with the ability to scale up to 100 tonnes per year. This is an initial production capacity of 26.6 tonnes per year, that can produce 26,666 1kg spools of filament. When the production is ramped up to 100 tonnes per year the production would be 100,000 1kg spools per year.

4.5 The AM market analysed

The financial data available for the AM industry is for the whole industry and covers the whole range of activities, from the printer manufacturers, software producers, service providers, filament producers to final printed products. The data also includes all the printable materials of which plastic is only one of them. At this time in volume, plastic is used the most, however the value in monetary terms for plastic is low compared to the monetary value of the other parts of the AM industry. In 2019 of the 582 companies surveyed 72% used polymers and 49% used metal, (Ernst & Young 2019). Filamentive (2021) provide some data analysis for the UK. At the time of writing this report, detailed data about the other three partner countries is not yet available. For the UK Filamentive estimate that by end of 2021 there was 232,000 3D printers in the UK, which on average use 12 kg of filament annually. This equates to 2.8 million 1kg reals or a market of 2800 tonnes of filament. The estimated yearly growth for the whole AM industry is given my Ernest & Young, and HUBS as approximately 25%. If this is assumed across the whole industry equally, then the plastic AM industry can be assumed to have a compound annual growth of 25%. This means that the amount of filaments required in the UK for 2025 will be 8.544 million 1kg reals, and for 2030 it will be 26.077 million 1kg reals. This is an exponential growth just for the UK. There is no breakdown of the types of polymers that are projected to be used in 2025 or 2030.

At the time of writing this report the manufacturing capacity for AM recycled filaments in the UK is very small, and most is imported. Filamentive, is one of the larger companies selling filaments in the UK, yet their product is manufactured in the Netherlands by a conglomerate based outside the EU. This means that the filament production expansion within the partner countries has a huge potential.

4.6 Potential for additional plants in partner countries

The full-scale plant that this project envisaged, had the maximum capacity of 100 tonnes per year. There was no indication which polymer types the plant was to produce. However as shown in Appendix 4, there are many types of plastics that can be used for AM. From data published by Filamentive (2021), their research found the most used plastic in 3D printing was PLA, which according to them was more than 95% of their market. The problem is that good clean PLA can usually only be found from post industrial waste, which is of high grade with low levels of contaminants and therefore easily recycled into filaments. The PLA from municipal waste is available but it is quite contaminated and costly to recycle to the purity needed to make sub 2mm filaments.

Axion polymers (axiongroup, 2022) in Manchester England, recycle approximately 200,000 tonnes of mixed plastics, and produce ABS, PP and polystyrene pellets that are used as a replacement for virgin plastics. Their plastic waste comes from motor vehicles and electrical and electronic consumer products. They only make the recycled plastic pellets, but do not turn them into filaments for AM. Just this one facility has the potential to provide feedstock for many 100 tonne filament plants in the UK. Furthermore, they recycle only 200,000 tonnes a year which is a fraction of the waste plastic potentially available in the UK. Attero (Attero, 2022a) is a company in the Netherlands that recycles plastic foils and produces 24,000 t of high quality LDPE pellets.

Therefore, there are great opportunities across NWE to partner with existing plastic pellet manufacturers and continue the recycling process by turning the pellets into filaments for the AM industry. Furthermore, given the amount of waste plastic that is not currently recycled, there is opportunity for many 100 tonne capacity plants to be set up all over NWE. The business model could be to focus on a small range of polymers like Axion and Attero have done and become a specialist filament manufacturer.

While it is not possible to put a number on the amount of 100 tonne facilities that could be made in NWE, given the millions of tonnes of waste plastic that are not yet recycled the potential is very large.

4.7 Circular economy in the AM industry

This project is based on a circular economy business model, which focuses on local recycling opportunities. This means that the feedstock for the AM pellet and filament plant should come from local municipal waste thus reducing the distance travelled. There is also the added benefit that local users of the filament know that they are using locally generated filament that they have saved from incineration or landfill. The size of the plant is chosen so that multiple smaller plants can be dotted around Europe rather than a few huge plants. Attero seem to have a large traveling footprint. The yearly distance used for transport of the sorted foils, which is carried out by Attero, is 4,800,000 km (Attero, 2022b). (This is from their website, it looks a large number, and they do not give more detail.)

Any small city that has the capacity to provide the waste plastic needed to supply a 100 tonnes capacity plant can be a potential city for a plant. What is unknown at this time is the plastic AM offtake or product market, i.e., where the exact market is for the filaments, as a wide range of commercial entities as well as hobbyists use the filaments. Given the projected compound growth of 25% per year there is the potential for early producers to help grow the market using a supply push model.

In the lab it was shown that the filaments were able to be reprocess up to 4 times, before there was a large reduction in the polymer chains that drastically reduced the workability of the plastic. This means that after four uses the plastic can be recycled through other pathways other than filament production. Chemicals that lengthen the polymer chain can be used or the plastic can be mixed with virgin plastic to make a few more production cycles. Otherwise, together with the 20% waste produced during production of filament, it can be forwarded to a company that carries out large AM print production, for example that carried out by 10-XL (10-xl, 2022), thus continuing the circularity of the plastic. As the TRANSFORM-CE project has shown, it will be possible to forward any plastic that is unsuitable for AM production to the IEM industry to continue the circular economic model.

5. Conclusions and recommendations

The criteria used to identify future sites for IEM plants were based on the Save Plastics' Green Plastic Factory in Almere the Netherlands. Almere, with its over two hundred thousand inhabitants, is able to supply 1000 t of low-grade plastic films per year. This means that any city or region with approximately 400,000 inhabitants can supply a single 2000 t plant. Extrapolating the capacity to all cities in the four regions it was found that at least 35 cities have 400,000 inhabitants. Added to this are cities with less than 400,000 inhabitants that will grow by 2030. Further plants could be made in places like capital cities where many millions of people live. It also does not take into consideration towns which individually do not have enough waste foils to feed an IEM plant, but being in close proximity to each other could, with a short travel distance, supply a 2000 t per annum plant. This implies that the number 35 is a rather conservative estimate. On the other side of the equation, the number 35 does not take into consideration factories within the four partner countries that are already opened. If 35 new 2000 t capacity plants were to open, that would divert from EfW and landfill, 158,000 t of waste plastic films per annum. This number is a small fraction of the 6 Mt of unrecycled waste plastic in these four countries.

The whole IEM business is niche and has a few large businesses across Europe. Therefore, statistics about volume or market capacity for the products produced is not available. However, given the amount of wooden, and metal products that could be substituted with solid plastic using IEM technology, there is huge potential growth for the IEM industry. This is especially true as this industry is in its infancy, and the amount of waste plastic in the recycling system is in the millions of tonnes

Many municipalities and states have a growing problem of what to do with their waste plastic. IEM offers a circular economy model for the local municipality to be involved in producing large scale products made from local waste that can be used by local consumers. Examples are street furniture and playground objects. The expansion of the IEM market will depend on support from public authorities and consumers creating the demand pull for the products and ingenuity on the part of the IEM manufacturers creating the supply push.

The whole AM market is expected to have a compound growth of approximately 25% per annum. This implies that there is an opportunity in NWE for local production of the filaments used to print AM products. Furthermore, the production runs for AM products are projected to increase to at least 1000 products from the current production run of less than ten. This implies a greater need for filaments and bodes well for the expansion of this market.

While it is not possible to put a number on the amount of 100 t AM filament facilities that could be made in NWE, given the millions of tonnes of waste plastic that are not yet recycled the potential is very large.

The potential to reuse the plastic multiple times for both the AM and IEM processes makes these industries perfect to operate on circular economy principles.

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Appendix 1: Large city populations in the four partner countries

Table 3 the largest 36 cities in the UK (The Geographist, 2022)

City	Population	City	Population	City	Population	City	Population
London	8,907,918	Leicester	470,965	Stoke-on-Trent	277,051	Bolton	202,369
Birmingham	1,153,717	Edinburgh	488,050	Southampton	269,231	Aberdeen	200,680
Glasgow	612,040	Leicester	470,965	Derby	263,933	Bournemouth	198,727
Liverpool	579,256	Coventry	369,127	Portsmouth	248,479	Norwich	195,761
Bristol	571,922	Bradford	361,046	Brighton	241,999	Swindon	191,314
Manchester	554,400	Cardiff	350,558	Plymouth	241,179	Swansea	184,436
Sheffield	544,402	Belfast	328,937	Northampton	229,815	Milton Keynes	184,105
Leeds	503,388	Nottingham	311,823	Reading	229,274	Southend-on-Sea	183,809
Edinburgh	488,050	Kingston upon Hull	288,671	Luton	222,907	Middlesbrough	176,991
Leicester	470,965	Newcastle upon Tyne	281,842	Wolverhampton	218,255		

Table 4 The largest 37 cities in the Germany (citymayors.com, 2022)

City	Population	UK City	Population	UK City	Population
Berlin	3,275,000	Dresden	473,300	Aachen	241,300
Hamburg	1,686,100	Bochum	388,100	Krefeld	238,000
München	1,185,400	Wuppertal	365,400	Halle	237,400
Köln	965,300	Bielefeld	320,900	Kiel	229,900
Frankfurt	648,000	Bonn	307,500	Magdeburg	224,100
Essen	588,800	Mannheim	306,100	Oberhausen	221,700
Dortmund	587,600	Karlsruhe	279,600	Lübeck	213,400
Stuttgart	581,100	Gelsenkirchen	276,200	Freiburg	206,300
Düsseldorf	568,900	Wiesbaden	269,200	Hagen	201,700
Bremen	527,900	Münster	265,900		
Hannover	516,300	Mönchengladbach	264,400		
Duisburg	513,400	Chemnitz	255,600		
Nürnberg	486,700	Augsburg	253,800		
Leipzig	486,100	Braunschweig	243,700		

Table 5 The largest 18 cities in The Netherlands (worldpopulationreview.com, 2022)

City	Population	The Netherlands	Population
Amsterdam	741,636	Nijmegen	158,732
Rotterdam	598,199	Enschede	153,655
The Hague	474,292	Haarlem	147,590
Utrecht	290,529	Arnhem	141,674
Eindhoven	209,620	Zaanstad	140,085
Tilburg	199,613	Amersfoort	139,914

Groningen	181,194	Apeldoorn	136,670
Almere Stad	176,432	's-Hertogenbosch	134,520
Breda	167,673	Hoofddorp	132,734

Table 6 The largest 7 cities in Belgium (geoba.se, 2022)

Belgium	Population
Brussels	1,019,022
Antwerpen	459,805
Gent	231,493
Charleroi	200,132
Liège	182,597
Brugge	116,709
Namur	106,284

Appendix 2: Acronyms

The Plastic Industry Association seven plastic categories

These are the seven types of plastic that are identified by the Plastic Industry Association that make up all the categories for plastic recycling.

1 PETE	Polyethylene Terephthalate (PETE or PET)
2 HDPE	High-Density Polyethylene (HDPE)
3 PVC	Polyvinyl Chloride (PVC)
4 LDPE	Low-Density Polyethylene (LDPE)
5 PP	Polypropylene (PP)
6 PS	Polystyrene or Styrofoam (PS)
7 OTHER	Miscellaneous plastics (includes: polycarbonate, polylactide, acrylic, acrylonitrile butadiene, styrene, fiberglass, and nylon)

Appendix 3: Glossary of Terms

Additive Manufacturing:

This is the process of turning a digitised three-dimensional model into a physical object ay adding layer upon layer of material to form the object.

Commercial waste:

Consists of waste from premises used mainly for the purposes of a trade or business or for the purpose of sport, recreation, education, or entertainment, this excludes household and industrial waste

Misthrow:

Waste that should not be in this waste stream, i.e., plastic put into general waste or contamination like organic matter placed in the plastic waste

Post-Consumer waste:

Post-consumer waste is the waste produced at the end of a consumer-product lifecycle, e.g. food and thin film packaging that tends to be dirty, within mixed wase and is difficult to recycle

Primary packaging:

This is the first layer of packaging, that has direct contact with the product. It is the one that the final customers interact with, like a cereal box or a wine bottle. Its purpose is to protect the actual product, but it is also an important marketing tool

Residual waste:

Non-hazardous waste material that cannot be re-used or recycled and needs to be sent to energy recovery or disposal in landfill.

Secondary packaging:

This is the middle layer of packaging, that protects the primary packaging. Used to pack together more individual products in an organized manner. Some examples could be the printed shrink film used for containing 12 cans of soda or the cardboard box that guards 12 jars with pickles

Transport /Transport packaging:

The outer layer of packaging placed for transportation, e.g., **plastic film wrapped around a pallet**

Valorisation:

This is a process of changing residues into energy or products with a much greater economic value, i.e. enhancing the value of the waste

Virgin plastic:

Plastic resin that has been newly created without any recycled materials. This type of plastic is produced (using natural gas or crude oil) in order to create brand new plastic products for the very first time

Waste fractions:

The grouping of waste according to its properties; plastic, wood, metal, biodegradable waste, earth, stones, etc

Appendix 4: Types of plastic used in additive manufacturing (AM)

The list below makes up the types of plastic filaments used in AM (Geyer et al., 2017; Simplify3D, 2022).

6.1.1 ABS (Acrylonitrile Butadiene Styrene)

It is a low-cost material with good mechanical properties. It is tough and impact resistance, and therefore good for printing durable parts that will hold up to extra usage and wear. It can withstand much higher temperatures before it begins to deform. This makes ABS products good for outdoor or high temperature applications. When printing with ABS, good ventilation is necessary, as the material tends to have a slight odour. ABS also tends to contract quite a bit as it cools, so controlling the temperature of the environment can have major benefits.

6.1.2 High-Density Polyethylene (HDPE)

It is light, flexible, easy to dye and mould, has good insulating property, and has a non-absorbent property that can be used for everyday materials. However, Garmulewicz et al. (2018, p. 118), explain that the thermal properties of HDPE make it hard to work with, and as of 2018 HDPE "… *commercially available HDPE filament from recycled materials is still hard to find*."

6.1.3 Low-density polyethylene (LDPE)

It is a polymer used in many different types of packaging. It can be used when wear resistance is a critical issue; for example, the soles of shoes also require hardness, plasticity, elasticity, and more. LDPE can also be used as a near-surface filler or in creating products like sliding pads (commonly used with furniture).

6.1.4 Polyethylene Terephthalate (PET)

It is used to manufacture water bottles. It is a semi-rigid material with good impact resistance, but it has a slightly softer surface which makes it prone to wear. The material also benefits from great thermal characteristics, allowing the plastic to cool efficiently with almost negligible warpage.

6.1.5 Polylactic Acid (PLA)

It is the filament of choice for many extrusion-based AM, because it is used at a low temperature and does not require a heated bed. It is inexpensive and creates parts that can be used for many applications. It is derived from crops such as corn and sugarcane, it is biodegradable and is therefore considered one of the most environmentally friendly filaments. For the PLA to be compostable it must be able to compost according to the European standard EN 13432. However, the conditions for composting under this standard are only suitable for commercial or industrial type composting and not ordinary ambient temperature garden composting.

6.1.6 Polypropylene (PP)

It is a semi-rigid and lightweight material used in storage and packaging applications. It is a challenging metrical to use for AM, however it is tough and has a good fatigue resistance making it ideal for low strength applications like living hinges, straps, leashes, etc.

About the project

The problems associated with plastic waste and in particular its adverse impacts on the environment are gaining importance and attention in politics, economics, science and the media. Although plastic is widely used and millions of plastic products are manufactured each year, only 30% of total plastic waste is collected for recycling. Since demand for plastic is expected to increase in the coming years, whilst resources are further depleted, it is important to utilise plastic waste in a resourceful way.

TRANSFORM-CE aims to convert single-use plastic waste into valuable new products. The project intends to divert an estimated 308.25 tonnes of plastic between 2020 and 2023. Two innovative technologies – intrusion-extrusion moulding (IEM) and additive manufacturing (AM) – will be used to turn plastic waste into recycled feedstock and new products. To support this, an R&D Centre (UK) and Prototyping Unit (BE) have been set up to develop and scale the production of recycled filaments for AM, whilst an Intrusion-Extrusion Moulding Facility, the Green Plastic Factory, has been established in the NL to expand the range of products manufactured using IEM.

Moreover, the project will help to increase the adoption of technology and uptake of recycled feedstock by businesses. This will be promoted through research into the current and future supply of single-use plastic waste from municipal sources, technical information on the materials and recycling processes, and circular business models. In-depth support will also be provided to a range of businesses across North-West Europe, whilst the insights generated through TRANSFORM-CE will be consolidated into an EU Plastic Circular Economy Roadmap to provide wider businesses with the 'know-how' necessary to replicate and up-scale the developed solutions.

Lead partner organisation
Manchester Metropolitan University

Partner organisations
Materia Nova
Social Environmental and Economic Solutions (SOENECS) Ltd
Gemeente Almere
Save Plastics
Technische Universiteit Delft
Hogeschool Utrecht
Hochschule Trier Umwelt-Campus Birkenfeld Institut für angewandtes Stoffstrommanagement (IfaS)
bCircular GmbH

Countries
UK | BE | NL | DE

Timeline
2019-2023

www.nweurope.eu/transform-ce