3DP-RDM
3D printing-enabled re-distributed manufacturing

Redistributing material supply chains for 3D printing

Project Report

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Executive summary

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In this study we investigate how materials supply be redistributed cost-effectively to bring materials production closer to primary goods production by using 3D printers, and how this could alter the global landscape of materials supply and manufacturing. The research forms part of the 3D printing enabled re-distributed manufacturing (3DP-RDM) feasibility studies which aims to explore possible areas of interest for future research projects supporting the 3D printing industry in the UK. We focus on plastics and to a lesser extent on metals since these two material groups are already used for 3D printing and they represent a diverse mix in usage, value, and production and recycling techniques.

The research has been divided into two stages. The first stage comprises a system study for London, which explores the material streams arising from London's waste, taking into account the amount, location and supply chain in the waste recycling processes. The second stage encompasses a stakeholder survey in which participants have been asked which barriers they perceive for using local materials for 3D printing, and to devise potential solutions to these barriers.

London's household waste stream contains 10% plastics corresponding to roughly 380,000 tonnes per annum. Plastic bottles and pots, tubs and trays (PTTs) represent 73% of the waste. PET (e.g. bottles) and HDPE (e.g. milk jugs and shampoo flasks) are the major plastics in the household waste stream, representing 49% and 19% of the total plastic packaging waste, respectively. Both materials are also widely recycled already, although UK recycling rates are still relatively low with 57% for plastic bottles and 30% for PTTs.

The main 3D print technology for these thermoplastics is material extrusion, in which a plastic filament on a spool is used to create a 3D object, layer by layer. With prices below £1,000, the 3D printers based on this technology are the cheapest in the broad range of 3D printers available, contributing to the wide distribution of these printers. However, due to current technology limitations, the quality of the mechanical properties of the 3D printed objects is low so these products are mainly used for prototyping, scale modelling or decorative purposes. The current price difference between raw plastic material and 3D print filament (of around £30 per kg) can make plastic recycling cost-effective.

PET bottles collected for recycling are ground into flakes. The yield of this process is in the range of 40% – 75%, depending on the amount of contamination in the waste stream. Part of this contamination is caused by the product itself such as glue, labels and caps of the bottles and potential residual liquid. Another part is caused by impurities due to mixing with other waste materials like metal cans and paper. Chemical recycling processes offer methods to produce premium PET material from PET waste, allowing for full recycling into primary products.

3D print filament is already produced commercially from recycled PET on a small scale, and the filament delivers good print results. The thermal properties of HDPE make the material harder to print as during the printing process thermal warping can occur, causing deformed 3D prints. In general, it is best to source the recycled material for the filament from homogeneous waste materials in order to prevent variances in impurities, densities and colours along the filament, which can have a negative impact on the print quality.

To assess the potential for using local materials, the existing waste streams in London have been studied. By examining the data on local authority collected plastic waste flows in London, it has been found that on average about a quarter of the waste is sent to reprocessing locations within London. After reprocessing, the recycled plastics is generally sent to manufacturers of plastic products such as packaging, but detailed data on material flows further down the supply chain are lacking.

Using local materials could reduce the environmental impact caused by the transportation of plastic waste. The CO_2 reduction potential is estimated to be 1,000 tonnes per annum, based on the average distances of the first reprocessing locations in the plastic recycling supply chain. Furthermore, the investigated data suggest that only 16% of the plastics in London's authority collected waste currently is recycled, so the overall landfill volume could be reduced by up to 8% if recycled plastics were used extensively in local printing operations.

Recycling plastic waste into 3D print filament is feasible and offers environmental benefits, such as increased recycling rates while reducing the amount of landfill and the CO_2 emissions caused by avoided waste transportation. Hence, if recycling material for 3D printing is feasible while offering environmental and economic benefits, which barriers prevent this from becoming mainstream? This question is central to the stakeholder survey.

In total twenty-four stakeholders consisting of academic people from engineering, design and business, and people from industry were asked about which barriers exist for using local materials for 3D printing. The barriers were divided into five categories: (1) economic, (2) technology, (3) social, (4) organisational and (5) regulatory. For each identified barrier the stakeholders were asked to rate the severity of the barrier and the likelihood to overcome them within predefined time periods.

Results show that most barriers are perceived to be related to economic or technological factors, with the latter being perceived as the most severe barrier. Technological barriers relate to the low quality and cost of 3D printed products, lacking standards and testing methods and the lack of small scale recycling technology. Economic barriers are related to existing economics of scale, which makes small scale recycling not cost-effective, and to the current players in the plastic recycling industry, which operate at a large scale, both on the supply as the demand side. Besides, the low price of virgin plastics (due to current low oil prices) threatens the plastic recycling industry as a whole.

Few barriers are seen as impossible to overcome. On average, the barriers are believed to be able to overcome within 3-4 years. This however does not mean that the local material supply is likely to happen soon since some important barriers seem to be difficult to tackle within years from now. One such barrier is the regulation of safety & health concerns about production processes and products using locally obtained materials, which is related to liability issues with 3D printed products from locally sourced materials.

Social barriers are related to limited (local available) knowledge and skills regarding 3D printing and also about how waste materials are valued and about sorting and recycling behaviour.

A number of proposals have been developed to overcome these barriers. Concerning technological barriers, ideas range from regulations governing technical standards and testing procedures to small devices to control/check the filament quality. Regarding economic barriers, financial incentives to recycle waste is seen as a way to stimulate this industry. Education, knowledge and skills sharing have been mentioned to improve local knowledge about (operating) 3D printers and suitable locally available materials.

Future challenges include technology improvements of the material extrusion technologies so that the quality of the products increases which will likely enhance the demand for these 3D printers, and in turn, the material.

The scope of this study has been limited to material extrusion, which covers only a small range of the 3D print market. Other 3D print technologies such as powder bed fusion allow for the manufacturing of products with high functional value. Focusing on this technology could offer other pathways to increase the use of local materials for 3D printing. However, this technology is several orders of magnitude more expensive and (as yet) reliant on virgin material that is not found in the waste stream (nylon). Future technologies may well be able to merge high-quality print results based on materials sourced from local waste streams.

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1 Introduction

1.1 Problem definition

The emerging market for 3D printers offers new opportunities to redistribute manufacturing; however, there is a broad lack of knowledge in how material supply chains may be part of this redistribution. The potential to change the location and scale of materials supply is critical to the question of how 3D printing relates to redistributed manufacturing. We ask: Can materials supply be redistributed to bring materials production closer to primary goods production? There are structural barriers to creating a circular economy of material flows, stemming from the large economies of scale in traditional manufacturing. Highly distributed yet valuable quantities of material waste, such as biomass, recyclable polymers, and metals, are predominantly sold into secondary materials markets rather than back into primary production. One main reason is that concentrations of valuable materials in waste are typically small compared to the amount of material needed for traditional manufacturing. When waste is aggregated in large recycling facilities, information and value is lost through mixing. The redistributive logic of 3D printing production, involving small batch customised production with near constant returns to scale in many markets, presents the possibility that 3D printing markets could be fed by small batch quantities of high quality waste, increasing the circulation of information and material value. This opens a compelling possibility that material supply chains could be redistributed, bringing the scales and locations of production and consumption closer.

Applying local materials for the manufacturing of goods is linked to what is called 'urban mining', it refers to the systematic reuse of materials from urban areas in order to improve the sustainability of cities, as described by Brunner [15]. In his article he notes that comprehensive information about materials and substances is essential to facilitate this transition. One of the barriers towards a local circular economy with respect to 3D printing is the lack of knowledge about the available local materials. To be able to use local materials it is necessary to know the material's quality (e.g. level of contamination), quantity, form (shape and physical state) and the location. The information is related to the final 3DP product, which demands a certain quality and quantity of a particular input material, schematically shown in Figure 1. The

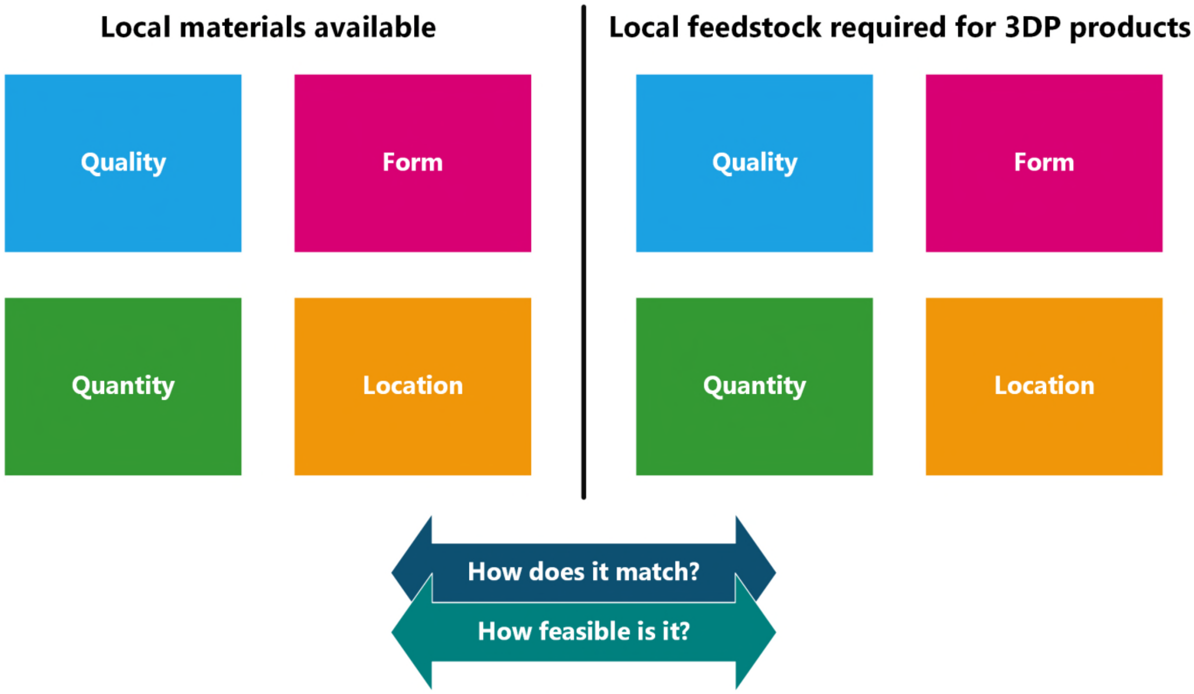


Figure 1: Matching local materials with 3D printing products

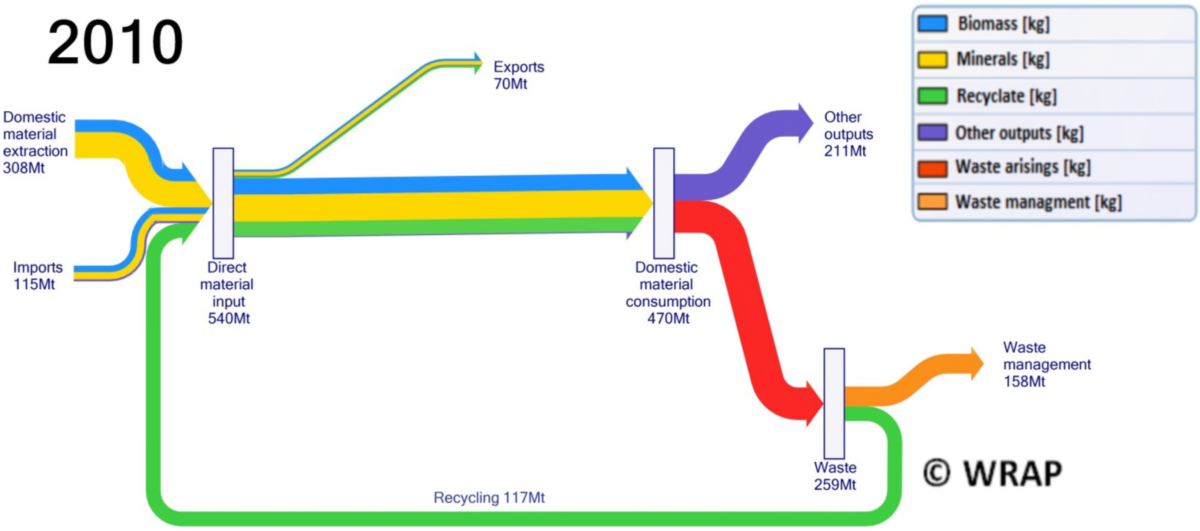


Figure 2: Sankey diagram of material flows in the UK in 2010 [8].

form and quality of the material will determine the required pre-processing steps. The location will determine the transportation cost which will help to determine its overall economic feasibility.

The information will support local manufacturing of goods and recycling processes. This will be enhanced by the digital nature of 3DP; software could eventually find the most optimal materials for a certain design. Since the product supply chains will transform from hardware-constrained to software-defined [16], information about local materials will become increasingly important.

A large part of the locally available materials can be found in waste streams. Based on a study from WRAP [8] waste amounts to 55% of the domestic material consumption in the UK in 2010, see Figure 2. Besides, since reusing and recycling waste is contributing to a more sustainable environment, waste is an interesting part of the local materials to study further.

Practical examples illuminate the nascent value of using local waste sources for 3D printing. The Ethical Filament Foundation [17], through partnerships between local filament producers and waste picker associations in India, created high quality certified filament by processing HDPE plastic from waste. The filament is manufactured locally, and is used for primary production. The profits from producing material feedstock, as well from the local production of goods from 3D printing, benefit local communities. This example points the way to the potential value for local economies in the UK if material supply was brought closer to the scale and location of consumption.

There may also be considerable environmental benefits. Waste management is a growing challenge in the UK. Creating new pathways for transforming waste into resources are critical, and may reduce carbon emissions from averted raw material extraction and transportation.

1.2 Societal relevance

Benefits for the UK economy of redistributed materials supply may include the increased control over materials for 3D printing companies, a premium on material value for waste management companies leading to a new enabler of the circular economy, and overall stimulus in local economies through increased markets in material reprocessing and production.

1.3 Study overview

The aim of this study is to explore the current opportunities and challenges of redistributing material supply chains for the use of 3D printing.

London has been selected for a case study in order to limit the scope of the research and to be able to analyse the current supply chains and markets in a local context. Besides, based on the total of 291 3D printers and 2,165 makers in London, it is currently (November 2015) the most popular city in Europe and the third in the world [10], making it an excellent location for this case study.

Additionally, to limit the scope further, this study will focus mainly on plastics and in a lesser extent on metals, because these two material groups are already used for 3D printing and they represent a diverse mix in usage, value, and production and recycling techniques.

The main research question in this study is: How can materials supply cost-effectively be redistributed to bring materials production closer to primary goods production by using 3D printers and how could this alter the global landscape of materials supply and manufacturing?

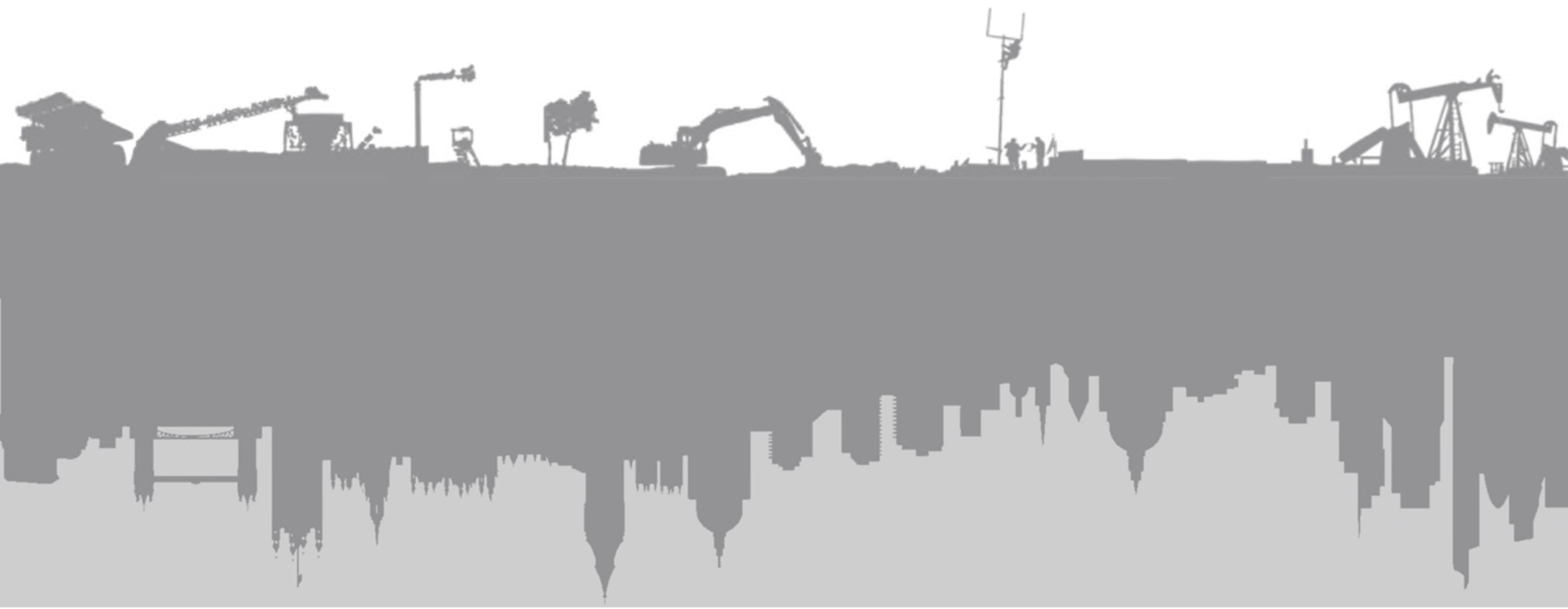
To find answers to the question the research will be divided into two stages.

The first stage is a combination of literature study, field trips and interviews which will be used in order to get an understanding of the current lay of the land related to 3D printing and local (waste) materials. This is followed by a system analysis approach focused on the plastic waste streams in London, taking into account the amount, location and supply chain in the waste recycling processes.

The second stage comprises a stakeholder survey in which participants will be asked which barriers they perceive for using local materials for 3D printing.

1.4 Outline of this report

The next Chapter will present some background information related to 3D printing technologies and materials, supply chains and some statistics about the waste in London. Chapter 3 will focus on the production, market and waste of plastic materials in the UK. Subsequently, Chapter 4 will describe current practices and some of the opportunities and challenges related to recycling plastics for 3D print filament. The next chapter, Chapter 5, will focus on the plastic waste streams within London and will discuss the current supply chain entities involved in the recycling of the plastic waste arising in London. Chapter 6 will discuss some other materials suitable for 3D printing and how this could change the supply chain. Then Chapter 7 will briefly present some business scenarios associated with the distribution of manufacturing regarding 3D printers and some of the implications. Chapter 8 will discuss the challenges and opportunities regarding the redistribution of material supply chains. Finally the conclusions are presented in Chapter 9.



2 Background

This chapter will give some background information about 3D printing, supply chains and general waste statistics of London.

2.1 3D printing

Additive manufacturing (AM) or 3D printing is a technology which ASTM has defined as [18]:

"A process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining".

The technology offers capabilities to produce products with complex shapes which are hard or impossible to produce with other manufacturing techniques. Besides, due to the nature of additive manufacturing, less material is wasted during the production phase. Furthermore, it is possible to adjust the internal structure of a product, offering opportunities to produce lighter products using less material.

2.1.1 Working principle

A digital representation of an object is created with computer aided design (CAD) software, the so-called 3D CAD model. This software file is converted to a .STL file in which the 3D model is divided into several horizontal layers. Subsequently, this file is used by a 3D printer to print these layers successively until the last layer has been completed and the final object created.

2.1.2 AM techniques

AM processes can be categorised by the type of material used, the deposition technique or by the way the material is fused or solidified. Process terminology is being defined by the ASTM F42 committee. The processes have been categorised into seven areas as follows [12]:

1. <u>Directed energy deposition</u>

Focused thermal energy is used to fuse materials by melting as the material is being deposited. In most cases, a laser is the source of the energy, and the material is a metal powder. More than one material can be deposited simultaneously, making functionally graded parts possible. Also, most directed energy deposition systems use a 4- or 5-axis motion system or a robotic arm to position the deposition head, so the build process is not limited to successive horizontal layers on parallel planes. This capability makes the process suitable for adding material to an existing part, such as repairing a worn part or tool.

2. <u>Powder bed fusion</u>

Powder bed fusion is a process by which thermal energy fuses selective regions of a powder bed. The source of the thermal energy is a laser or an electron beam. The thermal energy melts the powder material, which then changes to a solid phase as it cools. Both polymer and metal materials are available in powder bed fusion processes. For polymers, the unfused powder surrounding a part serves as a support. For metal parts, anchors are typically required to attach part(s) to a base plate and support down-facing surfaces. This is necessary because of the higher melting point of metal powders. Thermal gradients in the build chamber are high, which can lead to thermal stresses and warping if anchors are not used. Because powder bed fusion is a thermal process, warping, stresses, and heat-induced distortion are potential problems for all materials. Most of the available metal AM systems are powder bed fusion processes.

3. <u>Material extrusion</u>

Material extrusion-based fused deposition systems (FDM) use two spools of thermoplastic material; one is used for the build material and the second for the support material. It is relatively inexpensive (see Figure 3).

4. <u>Material jetting</u>

The material-jetting process uses inkjet-printing heads to deposit droplets of build material. Photopolymers or wax-like materials are used which are cured by UV light as they are being deposited. Multi-nozzle print heads are applied which increase the speed. Besides, it is possible to create a print with two different build materials simultaneously. One of the applications is to produce wax patterns for casting small metal parts.

5. Binder jetting

Binder jetting is a process by which a liquid bonding agent is selectively deposited through inkjet print head nozzles to join powder materials in a powder bed. The dispensed material is not build material, but a liquid that is deposited onto a bed of powder to hold the powder in the desired shape. The technology is suitable for metal or sand powder beds.

6. Sheet lamination

Sheet lamination is defined as a process in which sheets of material are bonded to form an object. Sheet materials can be adhesive-coated papers that form a plywood-like solid when laminated into a 3D object or metal tapes and foils that form metal parts.

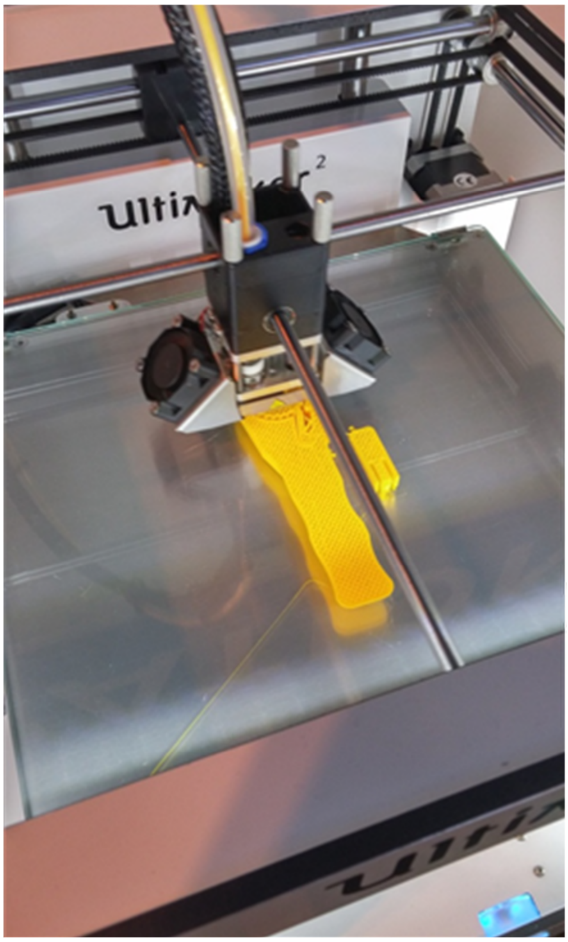


Figure 3: An example of a 3D printer using material extrusion.

7. Vat photopolymerisation

Vat photopolymerization is a process by which liquid photopolymer in a vat is selectively cured by light-activated polymerization.

2.1.3 Materials

The majority of materials used for 3D printing are plastics and metals. Ceramics and composites are used as well, besides a wide variety of materials are investigated and tested for 3D printing. In Table 1 an overview is given of the different 3DP techniques and the materials which can be applied.

A wide range of plastics can be used for 3D printing, depending on the applied AM technology.

For material extrusion thermoplastics such as ABS, PLA and PA (nylon) are applied. In recent years new filaments are developed based on polymer composites, such as the PLA filled with wood, bamboo, cork, copper and bronze.

In vat photopolymer processes thermoset plastics mainly in the form of resins are used, these are typically proprietary acrylic, acrylate, or epoxy materials.

In powder bed fusion processes polyamide powders - sometimes filled with glass, carbon or aluminium - are used in. Other polymers applied include polystyrene and polypropylene [12].

Metals used for suitable AM processes are aluminium, stainless steel, titanium, copper, cobalt alloys and brass. Silver and gold are applied as well. Metals are usually applied in powder form.

Table 1 – Process/material matrix

AM processes		Directed energy deposition	Powder bed fusion	Materials extrusion	Materials jetting	Binder jetting	Sheet lamination	Vat photopoly-merization
Materials	Plastic		X	X	X	X	X	X
	Metals	X	X			X	X	
	Graded/hybrid metals	X					X	
	Ceramics	X	X			X		
	Composites	X	X			X		X
	Investment casting patterns		X		X	X		X
	Others		Sand, wax, photo-polymer	Sand	Sand		Paper	Resin, liquid photo-polymer
Energy source		Laser, electron beam	Laser, electron or ion beam	Heating coil	Heating coil, UV light	N/A	Laser, ultrasonic	UV light, X-ray or y-rays
Relevant terms		LENS, DMD, LBMD, EBF3, DLF, LFF, LC, CMB, IFF	SLS, SLM, DMLS, DMP, EBM, SPS, Laser cusing	FDM, FFF, FLM	Inkjet, PolyJet, MJM, Aerosol Jet, ThermoJet	3DP, LPS, DSPC	LOM, UC, UAM	SL, SLA, MPSL, DLP, FTI
Part durability		← High						Low
Detail precision		High						Low →
Surface roughness		← High						Low
Build speed		Slow	Slow	Medium	Medium	Fast	Fast	Medium
Cost[1]		High	High	Low	Low	Medium	Medium	Medium
Support		No	Yes	Yes	Yes	No	No	Yes
Post-process		Yes	Yes	Minimum	Minimum	Yes	Yes	No

3DP, 3-Dimensional Printing
CMB, Controlled Metal Build-up
DLF, Directed Light Fabrication
DLP, Digital Light Processing
DMD, Direct Metal Deposition
DMLS, Direct Metal Laser Sintering
DMP, Direct Metal Printing
DSPC, Direct Shell Production Casting
EBF3, Electron Beam Freeform Fabrication
EBM, Electron Beam Melting
FDM, Fused Deposition Modelling
FFF, Fused Filament Fabrication
FLM, Fused Layer Modelling/Manufacturing
FTI, Film Transfer Imaging
IFF, Ion Fusing Formation
LBMD, Laser-based Metal Deposition
LC, Laser Consolidation
LENS, Laser Engineered Net Shaping
LFF, Laser Freedom Fabrication
LOM, Laminated Object Manufacturing
LPS, Liquid Phase Sintering
MJM, Multi-Jet Modelling
MPSL, Mask Projection Stereolithography
SL, Stereolithography
SLA, Stereolithography Apparatus
SLM, Selective Laser Melting
SLS, Selective Laser Sintering
SPS, Spark Plasma Sintering
UAM, Ultrasonic AM
UC, Ultrasonic Consolidation

Sources: Wohlers Associates, Inc. [12] and DNV-GL [19]

[1] Cost of AM machines, materials feedstock, and regular maintenance

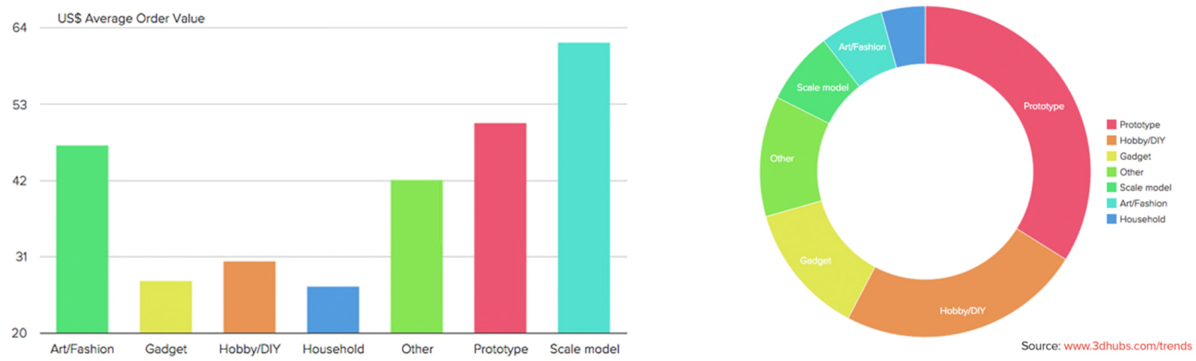


Figure 4: Popular print categories based on the 3D Hubs trend report for November 2015 [10].

2.1.4 Market

3D printing started as a suitable technology for rapid prototyping, Figure 4 shows that scale models and prototypes still dominate the market. This is confirmed by a survey of more than 100 industrial manufacturers by PwC in the beginning of 2014, showing that two-thirds were already using 3D printing, mostly for experimenting (43%) and prototyping only (37%) [20]. However, the same study shows that roughly 14% of the companies using 3D printing already use it for prototyping and production. Besides, 5% of these companies use it for the production of products.

A survey under industrial AM companies and service providers by Wohlers Associates shows that consumer products/electronics is the leading industrial sector with a share of 22% based on revenue [12]. A worldwide survey conducted by Gartner, Inc. in 2014 shows how organizations are using or planning to use 3D printing technologies, the results are shown in Figure 5.

Next to companies, 3D printers can be owned by individuals and makerspaces. Owners can share their 3D printer online with others who would like to print a product but do not own a 3D printer, forming so-called 3D printing hubs [10]. Local 3D printing hubs are product-service systems which offer products such as 3D printed objects and 3D printing filament and services such as designing and printing customized 3D objects. Here, 3D printers are shared among different users increasing its product use efficiency. Although

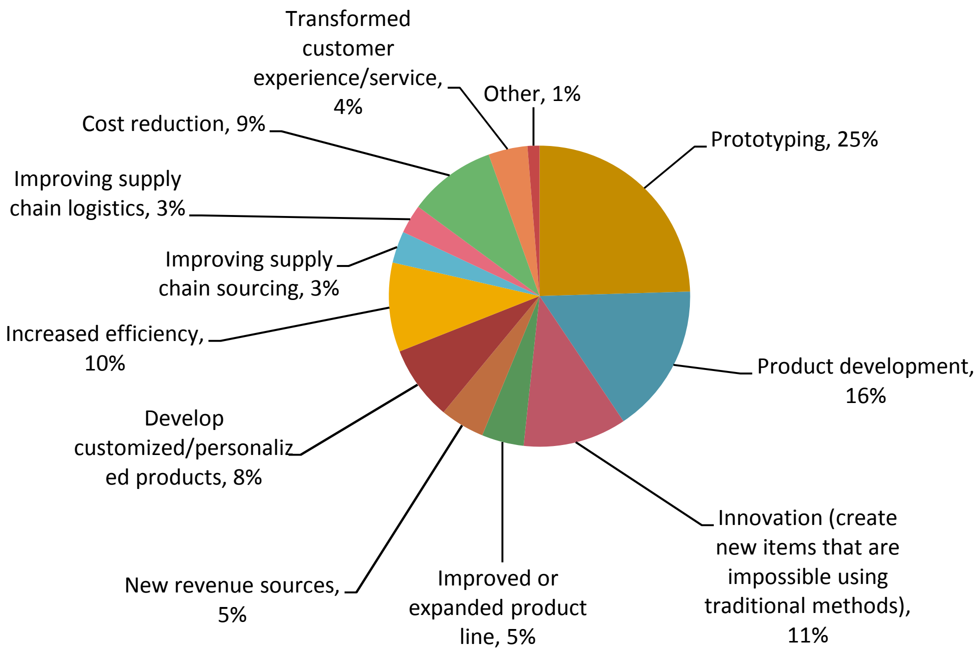


Figure 5: Reasons for pursuing 3D printing, source: Gartner (November 2014) [11].

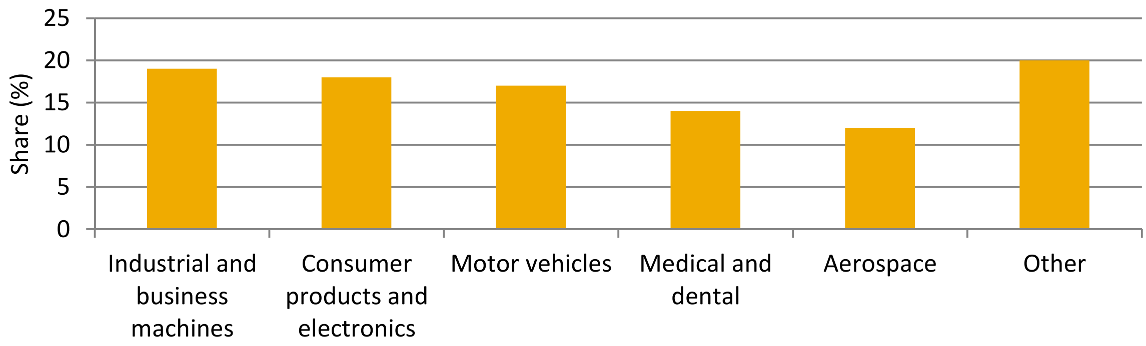


Figure 6: Share of additive manufacturing equipment sales by industry (%) [14]

detailed data on material usage for 3D printing is lacking, it is assumed that the current material use for 3D printers is relatively small due to the low production speed and the inherent material efficiency of 3D printers, however it is expected that the usage of 3D printing will grow in the near future. This is supported by the increase of the number of desktop 3D printers sold in the past years, from 66 in 2007 to 139,584 in 2014 [12, 21].

The global annual revenue from AM increased from roughly \$0.5B in 2000 to \$3B in 2013 (Figure 7, left) and it is expected that this will increase to \$7.3B in 2016 and to reach \$21.2B in 2020 [21]. The total AM material sales increased from \$71M in 2001 to \$423M in 2012. As can be seen in Figure 7 (right), photopolymers are responsible for roughly the half of the material sales.

Additive manufacturing is adopted in a wide range of industries, especially in consumer products, automotive, medical industry and aerospace [14], see Figure 6.

2.1.5 Limitations

Current limitations are the cost, manufacturing speed, quality and the limited amount of materials suitable for 3D printing. Furthermore, mixing of various materials into one 3DP product is still a challenge.

One of the major limitations of 3D printers is the production time, therefore most applications are aimed at prototyping and scale modelling rather than large-scale production. Nowadays, most final products made with 3D printers are either custom products like fitted hearing aids or products which are hard or impossible to produce with conventional techniques. Besides, most low-cost

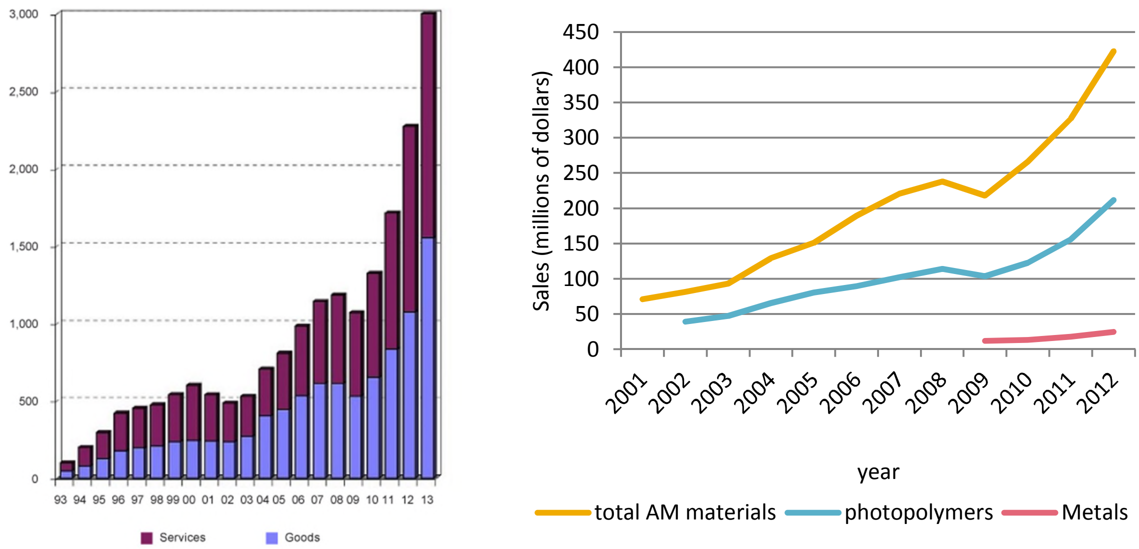


Figure 7: Global annual revenues from AM in millions of US dollars (left), source: Wohlers Report 2014. Estimated AM materials sales (right) [12].

3D printers are based on material extrusion and can only print one or two materials, which limits the applications.

2.2 Supply chains

2.2.1 The general concept

A supply chain is defined as "a set of three or more entities (organizations or individuals) directly involved in the upstream and downstream flows of products, services, finances, and/or information from a source to a customer" [22]. In general a supply chain consists of suppliers, manufactures, logistics, retail and consumers. In Figure 8 the main processes involved in the supply chain of traditional products including the end-of-life phase are shown.

After recycling, the raw material can either be used for the same product or for other products. This study focuses mainly on the processes from recycling to production. Dependent on the specific material or product, different processes may be involved in this part.

2.2.2 Redistributed additive manufacturing

With 3D printers, most of the processes of the general supply chain still apply, however some processes will get less important and some can be removed completely. Looking at the manufacturing, less raw material is required, fewer pre-processing steps are needed and in some cases a complex part can be printed at once, removing the need for assembly. Besides, when the production becomes more distributed, storage can be largely eliminated since the product can be produced at the time and location required.

In Figure 10 a schematic view of different forms of distributed additive manufacturing (AM) is shown. The number of dots indicates the number of entities in an average supply chain. So, for conventional manufacturing, there is one manufacturer producing the final product. Related to that product there are multiple component suppliers, which in turn make use of a wider range of material suppliers. The final product will be distributed via some distribution networks to a larger number of retailers where the product can be sold to a larger number of customers. The location in the supply chain where the final manufacturing step takes place is indicated with red dots.

For Central AM, the distribution of manufacturing locations does not change compared with conventional manufacturing. Because AM could potentially eliminate the need for components, component suppliers could become obsolete. With Distributed AM, manufacturing will take place in more locations closer to the customer. As manufacturing itself becomes more distributed,

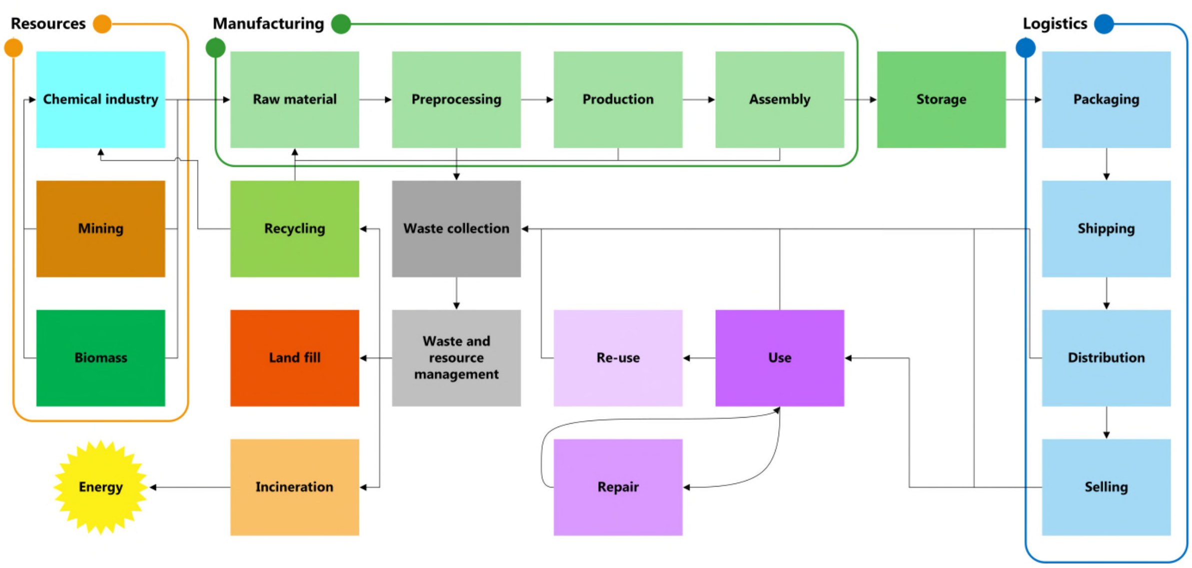


Figure 8: General supply chain of traditional manufacturing

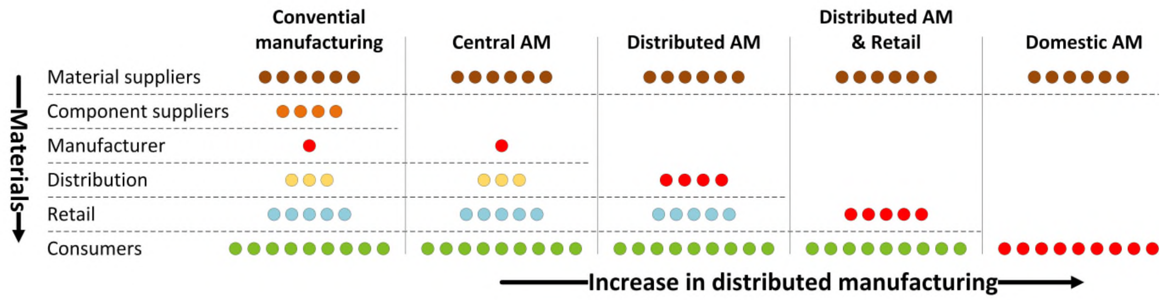


Figure 10: Different forms of distributed additive manufacturing and possible implications for the supply chain.

the distribution of products becomes less important. One step further, AM could be combined with retail, bringing the manufacturing even closer to the customer. Finally, AM could be applied at home, in which only the feed materials should be distributed.

Depending on how local manufacturing will become, the storage and logistics of products can be reduced significantly. Logically, production at the required location will remove the need for logistics completely, but it is questionable whether this will become the standard. At least, products can be produced more locally, eliminating the need for transportation of goods over long distances. This offers opportunities to lessen the amount of packaging for shipping which will likely mainly affect tertiary packaging. However, although AM offers potential to reduce costs, it can also lead to some cost increases. For example, less standardized products could increase the amount of packaging materials. Besides, the logistics of raw materials in centralised manufacturing is probably more efficient, since this can be done in large quantities to a limited number of locations. Therefore with the possible distribution of manufacturing, the redistribution of materials becomes an important aspect.

Material flows could potentially be redistributed, adding to the decrease of transportation. Besides, products ending up in the centralised waste streams increase the cost, time and energy to sort the materials. Moreover, some recyclable materials will be sent to landfill or will be incinerated, because they are currently hard to sort or mixed with other materials. Therefore, distributed material recycling could offer opportunities to reduce the amount of waste centrally processed and could increase the recycle rate at the same time.

2.3 Waste in London

Although the focus of this study will be mainly on plastics, this part starts with an overview of the total waste arising in London in order to put the plastic waste flows into context. London's waste streams can be divided into three categories:

1. Local Authority Collected Waste (LACW), previously known as municipal waste
2. Commercial and industrial (C&I) waste
3. Construction, demolition and excavation (CDE) waste

In 2008 London generated a total of 20 million tonnes of waste. With approx. 4 million tonnes, LACW accounted for roughly 20% of the total waste, C&I for 33% and CDE for the remainder of 48% [6]. A large share of the C&I waste consists of

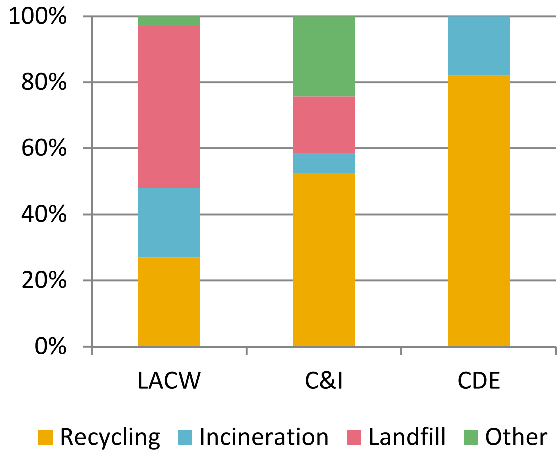


Figure 9: Waste management strategies per waste category for London in 2008 [6]

general mixed waste.

In Figure 9 the waste management method shows how the waste in London is processed. As can be seen, the majority of the LACW is sent to landfill; roughly a quarter is recycled or composted.

2.3.1 Local Authority Collected Waste

In 2009/2010, London produced 3.8 Mt of municipal waste. Household waste makes up 79%, the rest comes from small and medium-sized businesses [7]. The composition of the municipal waste is shown in Figure 11.

Plastics account for 10% of the total municipal waste, corresponding to roughly 380,000 tonnes of waste.

The share of the recycling/composing waste stream that goes to recycling differs greatly in London; overall recycling rates vary between roughly 12 – 33%. About 77% of London's landfilled waste goes to sites outside London; the reuse and recycling centres are distributed over London itself [7].

2.4 Conclusions

The different 3D print processes offer a wide range of applications and materials to be used. Due to current limitations, 3D printing is still mainly used for prototyping and scale modelling, however there are indications that this will shift more towards the production of (final) products in the near future. This will open opportunities to distribute manufacturing.

The supply chain of products covers a broad range of entities: raw material suppliers, manufactures, logistics, retailers, end-users to waste recycling companies. All of these entities could be influenced as manufacturing and materials become more distributed.

Waste materials can be recycled for 3D printing material. London produces about 20 million tonnes of waste annually, of which about 20% comes from municipal waste. About 50% of this total waste is still sent to landfill. A yearly amount of roughly 380,000 tonnes of plastic waste arises in the municipal waste stream of London.

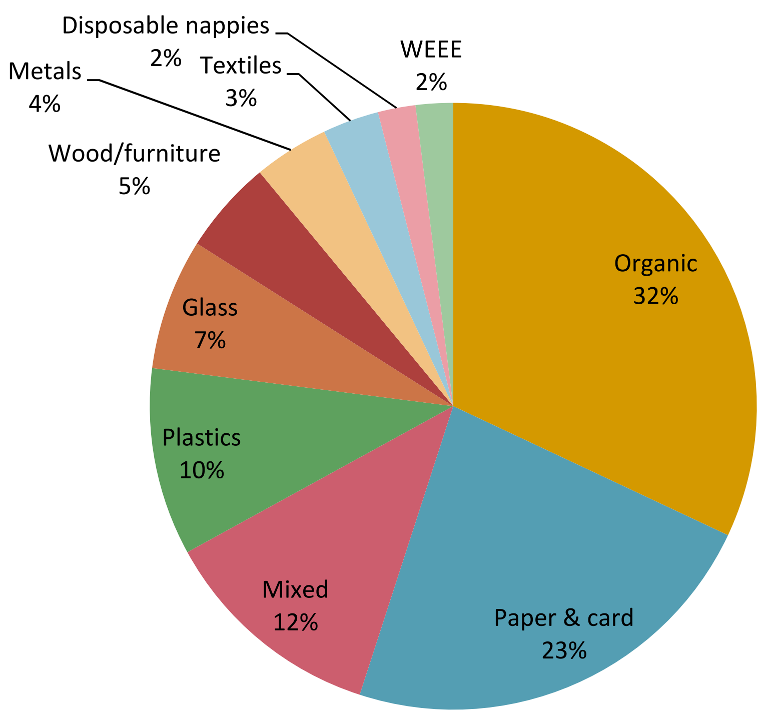


Figure 11: Municipal waste of London by material based on weight, data from Defra, 2010 [7].

3 Plastics production, waste and recycling

In this chapter the focus will be on statistics related to the production, uses and waste recycling techniques for plastics for the UK in general.

3.1 Plastics demand

In 2012 the UK produced 2.5 million tonnes of plastic, representing roughly 1% of the global production [23]. In Figure 12 the European plastics demand by segment and polymer type is shown [5].

The share of plastic use per segment is quite similar for the UK. The UK processes more than four million tonnes of plastics per year. About 40% of the plastics are used for single-use diposable applications, such as packaging, agricultrual films and consumer items, building and construction purposes are between 20 and 25%, 6% is for automotive use [23]. From Figure 12 it can be seen that PET is mainly applied in the packaging industry.

A survey of household plastics by RECOUP in 2015 [2] shows data about the total consumption and collection of plastic packaging in the UK in 2014/2015, see Table 2. Next to these presented data, plastic films account for 415,000 tonnes and it is estimated that the total amount of non-consumer plastics is roughly 726,000 tonnes [2]. The overall amount of plastics placed onto the market (POM) is therefore 2,260,000 tonnes. Of the Local Authorities (LA) in the UK, 98% do have a collection provision for bottles; for plastic Pots, Tubs and Trays (PTT) this is 75% and for plastic films 20% [2].

Specific data on the type of plastics in the waste stream is lacking, however RECOUP estimated this composition based on the amounts of plastics from a Packaging Market Study (Plastic Flow) commissioned by Valpak Limited and Defra in 2014 [24] and the polymer breakdown from the Plastics Packaging Composition 2011 report [25]. In Figure 13 the results are shown.

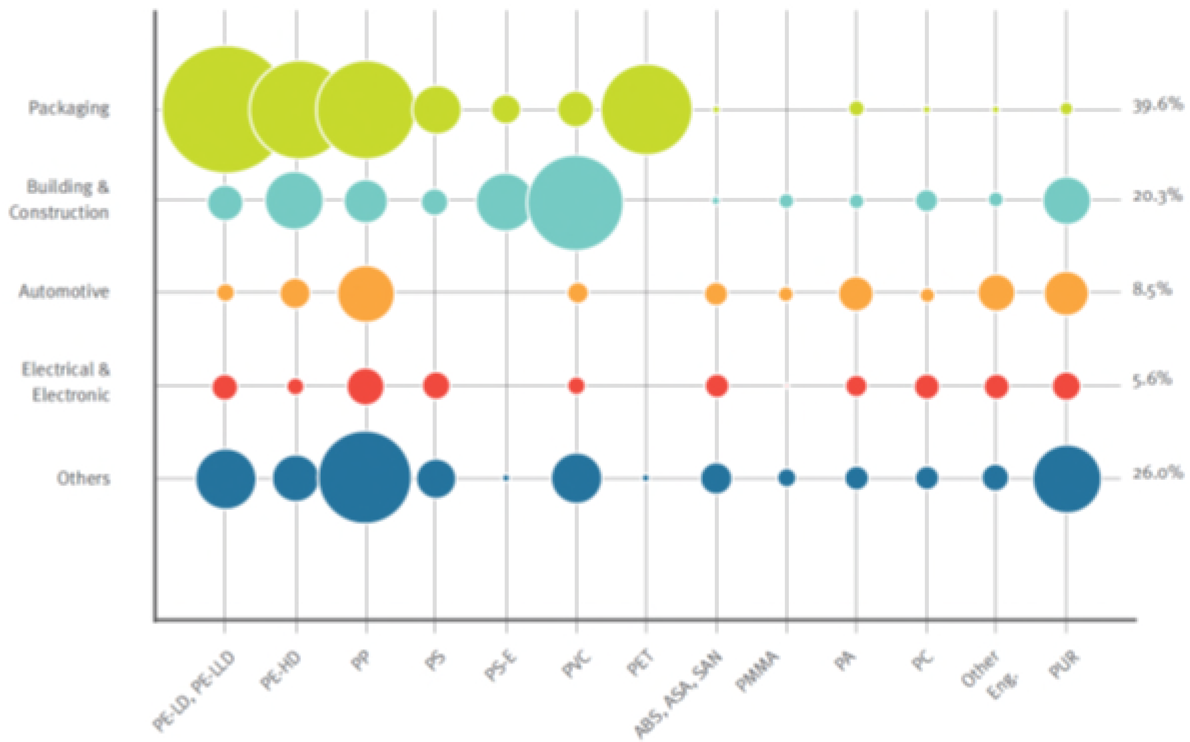


Figure 12: European plastics demand by segment and polymer type, based on data from 2013 [5]

Table 2: Tonnages of rigid plastic household packaging in the UK in 2014/2015 [2]

	Plastic bottles	Plastic PTT	Overall rigid plastic packaging
Consumption	594,000	525,000	1,119,000
Collection	337,447	155,176	492,623
Recycling rate	57%	30%	44%

The UK non-consumer packaging consists mainly of LDPE/LLDPE films, which accounts for 55% of the total [25].

The majority of UK domestic mixed plastics packaging is collected in residual waste and is landfilled. To decrease the share of waste to landfill and stimulate recycling, the UK government has increased the cost of landfill over the last decades. The landfill tax rose from around £10 in 2000 to £32 in 2008 and to the current rate of £82.60 per tonne in 2015. Combined with the median gate fee for waste sent to landfill of £20 in 2015 [26], the total cost of landfill is more than £100 per tonne.

3.2 Recycling of plastics

To get a better understanding of the current plastic waste collection/recycling process, a brief overview will be presented here. In Figure 14 a schematic diagram shows the different processes in plastic recycling. Plastics from municipal solid waste (MSW) are usually collected from kerbside recycling bins or drop-off sites. The collected waste is sent to material recovery facility (MRF), where the materials are sorted by plastic type, baled, and sent to a reclaiming facility. At the facility, any trash or dirt is sorted out, plastics are then further sorted based on colour and plastic type, often near infrared (NIR) light is used to sort plastics. Next, the sorted plastics are cleaned and turned into flakes. The flakes could be sold or could be turned into pellets before being sold to a plastic product manufacturer. The recycled plastics could be used in a wide variety of products, from clothing to packaging materials. In the case of packaging materials, the plastic is used in a final product (e.g. food packaging), before it is being sold to the end-user/customer. After using the product, the plastic waste will be collected again.

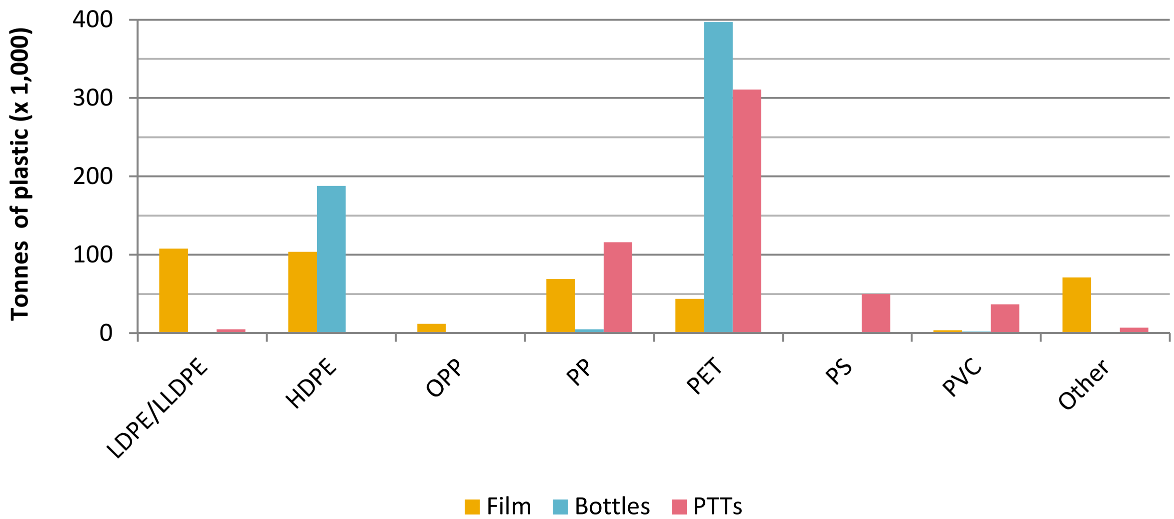


Figure 13: Consumer plastics packaging consumption by format and polymer type [2].

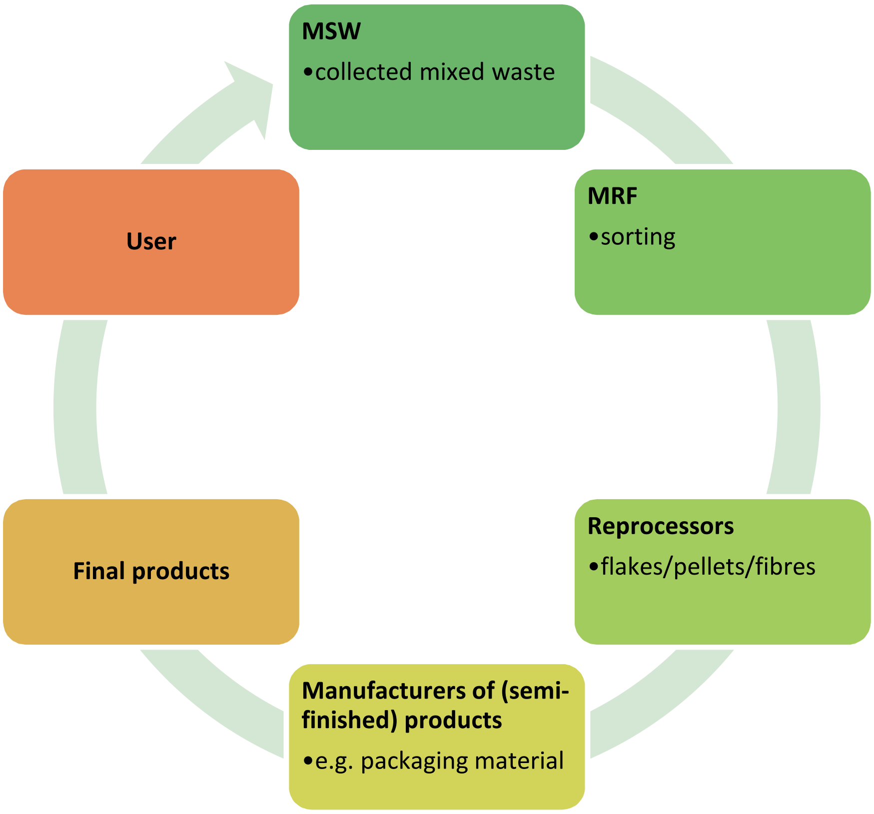


Figure 14: Simplified scheme of the circulation of plastic material.

In the UK mainly PET and HDPE bottles are recycled; other mixed plastics will mostly go to landfill or energy recovery [27]. About 45% - 52% of the plastic bottles are collected for recycling in the UK [28, 29].

3.2.1 Bottle recycling

The PET bottles are washed and ground into small flakes. After intensive washing, a flotation tank may be used to further separate the stream based on their different densities. The PET flakes are then dried and packed for dispatch [3]. The PET flakes can be reprocessed to make new PET bottles, or spun into polyester fibre.

The HDPE bottles follow a similar path, first the plastic is granulated and separated based on the density. Subsequently, the flakes are washed and

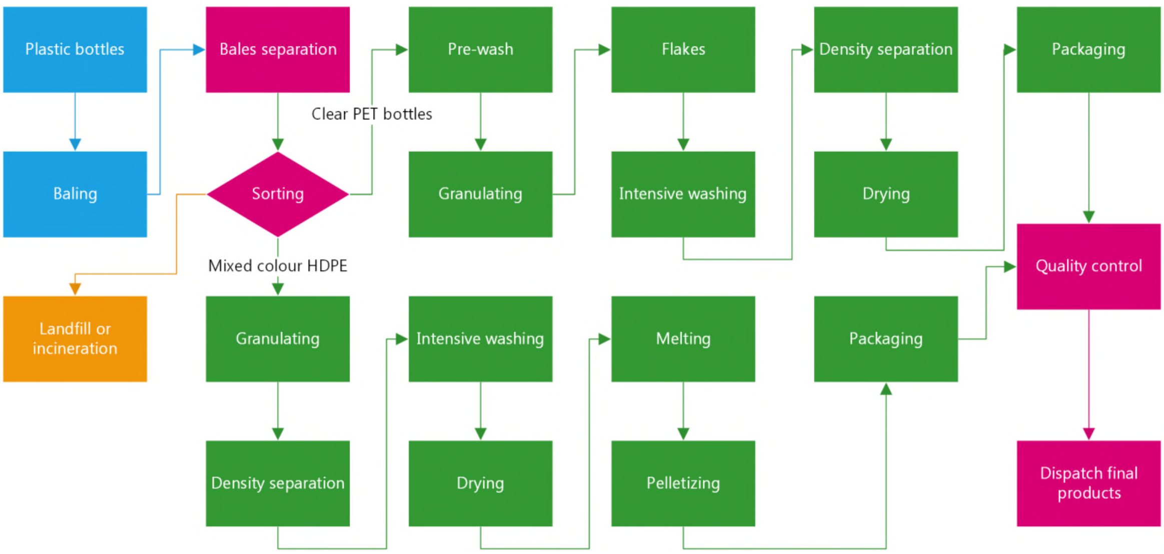


Figure 15: Schematic scheme of the plastic recycling process steps [3]

Table 3: End market destination of plastic waste [2]

End market destination	Plastic bottles	Plastic Pots, Tubs and Trays	Plastic film	Non-packaging Plastics
UK	62%	44%	15%	22%
Export (EU)	9%	16%	15%	14%
Unknown	28%	39%	70%	64%

dried. Then the dried flakes will be melted and formed into pellets, see Figure 15 for a schematic scheme. The pellets are shipped to product manufacturing plants, where they are made into new plastic products.

The material efficiency of processing baled PET bottles into flakes is roughly 75% [30], however depending on the contamination of the baled PET bottles the yield can be as low as 45%. By-products range roughly between 10-20% of the baled bottles and roughly 20% is waste which includes labels, glue and drinking liquids.

During recycling of PET the molecular weight reduces, via the so-called solid state polymerisation (SSP) process the molecular weight can be increased [31].

3.2.2 Quality of recycled PET

A study from WRAP on the quality of recycled PET [32] shows that UK converters of PET waste into recycled PET (rPET) report a wide variation in the quality across their suppliers, specifically rPET discolouration due to the variation in colour is a concern. The presence of small coloured PET particles in clear PET flakes contributes significantly to the discolouration. Besides, contaminants of other plastics and residual fragments of metals increase the general degradation of the material. Furthermore, PVC is a challenging contaminant to remove from PET flakes which impacts rPET quality, colour and properties. Even at small concentration (i.e. 100 ppm), PVC can form acids that break down PET [31].

3.3 Market for recycled plastics

There is a strong market for plastic bottles in the UK and export markets. The demand for plastic bottles is high and Local Authorities (LA) do not have issues with finding end markets. Although the demand for PTT is low, 78% of the LA do not struggle to find a market, it is expected that a significant proportion will be exported to non-EU markets [2]. For plastic film and non-packaging plastics 50% and 55% of the LA struggle to find a market for it [2]. Table 3 shows information on the end market destination of plastic waste from the UK. As it can be seen, the majority of plastic bottles finds its way to locations in the UK.

To be less dependent on suppliers and converters, both the MRF and the reclaiming facility have multiple suppliers.

3.3.1 Price of recycled plastics

In Figure 16 the average monthly prices of various baled plastic bottles are shown for the period January 2001 – September 2015. Depending on the quality, the prices can be slightly higher or lower.

HDPE bottles are natural uncoloured bottles, such as milk jugs. HDPE mixed contain coloured bottles such as shampoo and detergent containers. Besides, based on information from one of London's MRFs, LDPE is currently recycled as well, but at a cost of £20 per tonne.

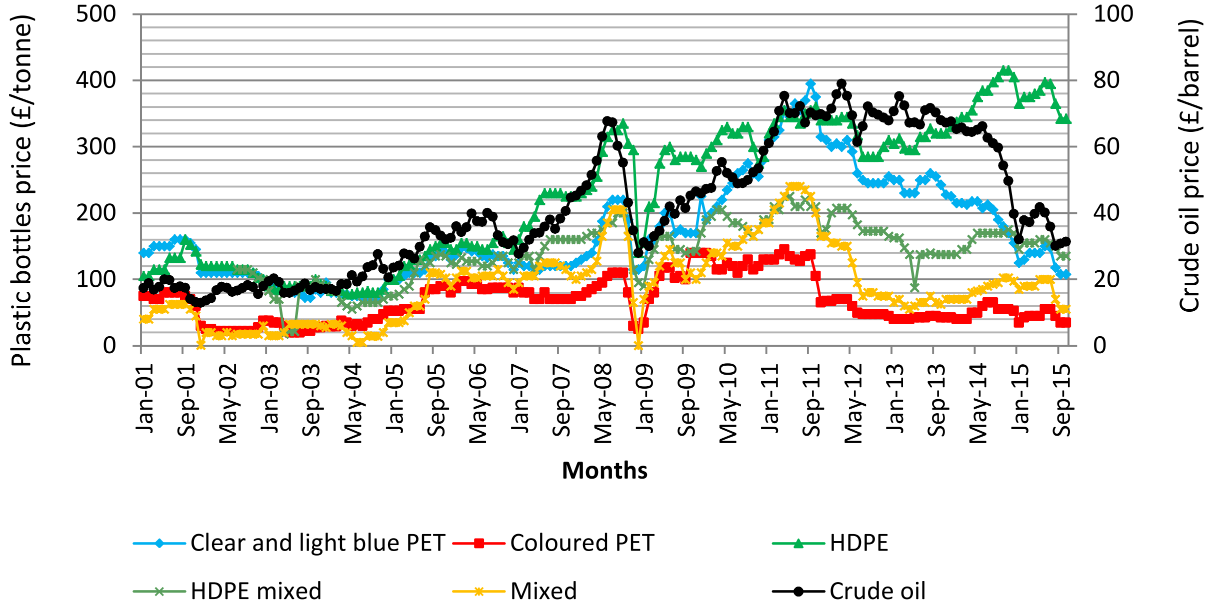


Figure 16: Average monthly prices of baled plastic bottles and crude oil prices [9]

Virgin polymer prices are one of the key determinants of recovered plastics prices [33], which can be observed by the relation with the crude oil prices in Figure 16. Since the processing of recycled plastic flakes or pellets is costlier, recycled plastics should be at least roughly £100 pounds per tonne cheaper than the virgin material. With the current decrease of crude oil prices virgin plastics may even become cheaper than recycled plastics; this trend threatens the recycled plastic market.

3.4 Conclusions

From the waste perspective, plastics are of particular interest to be used as locally recycled material. Plastic recycling rates are still low and the low density of the material causes higher transportation costs compared with other materials. From a distributed material perspective, plastics are highly distributed already, since they can be found in many common products.

The plastics PET and HDPE are already largely recycled and huge quantities exist in the household waste stream, mainly in the form of plastic bottles. There is a strong market for recycled plastic bottles, but decreasing oil prices may impact the plastic recycling market, since the price difference with virgin plastics becomes smaller.

About 45% - 52% of the plastic bottles are collected for recycling in the UK, suggesting that a large amount of plastic bottles is still hard to sort out from the waste streams.

4 Plastics recycling for 3D printing material

This chapter will discuss some studies and their findings about recycling plastic household products to produce filament to be used for 3D printing.

4.1 Introduction

The idea of recycling materials for 3D printing is not new. Producing feedstock from waste plastic lowers the costs and reduces the environmental impact of rapid prototyping [34]. Besides, recycling waste in-house can decrease the greenhouse gas emissions associated with the collection, transport and transfer of recyclable waste [35]. There are several projects which studied the use of recycled plastics for 3D printing and some waste plastic extruders are commercially available, like the open-source Filabot [1] (Figure 17), Filastruder, Filafab, RecycleBots, the MiniRecycleBot and the Lyman filament extruder.

Figure 17: The filament extruder Filabot [1]

Some companies sell recycled filament already. A Dutch company called Refil[2] is selling recycled ABS and PET filament and 3D printed products based on recycled material. They make use of an existing plastic recycling system for their materials. For the PET filament, they make use of recycled PET bottles. Another company, Fila-cycle, applies – among others – ABS and HIPS waste from the automotive industry to produce filament.

Drinks brand Coca-Cola and musician Will.i.am collaborated to produce objects using filament made from recycled plastic bottles, using the Ekocycle 3D printer from 3D Systems Inc.

In the developing world and in rural areas recycling plastic waste for 3D printing offers viable alternatives to centralized recycling [36]. Some organisations such as the Ethical Filament Foundation work together with local waste pickers, industry and entrepreneurs to create more value for the local community by producing 3D printer filament out of recycled waste.

A study by Wittbrodt et al. [37] compared the costs of 20 open-source designs printable on a RepRap with retail prices of similar products. Their findings show that it is economically attractive to invest in an open-source 3D printer for households in the US. This offers the potential for rapid growth of distributed manufacturing.

4.2 Process parameters and issues

4.2.1 General procedures and issues

To create filament from plastic household waste, the waste plastic item has first to be cleaned before it is cut in smaller pieces which are further grinded into small flakes. Subsequently, the flakes are heated and a screw will move the material through a heated barrel where it is compressed, melted, mixed and forced through a die to give the filament its shape.

Most 3D printers use filament with a diameter of 1.75mm or 3mm. To ensure that the filament can be fed into the 3D printer, the diameter of the filament is important. Besides, a constant density of the material is required to support a steady extrusion rate and high quality prints [35].

The final 3D products can be post processed in order to get a better aesthetic quality. Some ways to improve the final product appearance are sanding, polishing and painting [37].

[2] Refil BV, http://www.re-filament.com/

4.2.2 PET

Some companies produce recycled PET filament already. PET can be recycled in various ways using mechanical or chemical recycling [31, 38]. Mechanical recycling by grinding down PET bottles results in amorphous PET. Using this amorphous PET to produce filament directly would produce a low quality material which can result in the crystallisation of the material in the nozzle of the 3D printer after printing.

To get high quality PET, chemical recycling is used in which the recycled PET is depolymerized and purified before it is reused as raw material for the production of PET products. One chemical process to depolymerize PET is glycolysis. During this process the PET scrap is contacted with ethylene glycol in a wide range of temperatures (453-523 K) during a time period of 0.5-8 hours, using zinc acetate as a catalyst [38]. The main product of glycolysis is the monomer of PET, bis(hydroxyethyl)terephthalate (BHET), which can be polymerized after purification to produce PET again [38].

The recycled filament from Refil consists of 90% recycled material. Delivering the same quality and properties for the filament based on different batches of PET bottles remains the biggest issue. Controlling the quality, contamination level and colour variation of the input material is important and Refil uses currently Reach and RoHS data and visual inspection for this purpose. The company is working on a system to determine the material characteristics.

A half-litre single-serve PET water bottle weighs about 10g. Based on a specific density of 1,380 kg/m^3 for PET and assuming no material losses, such a bottle can be recycled into about 1.2 or 3.0 meter of filament with a diameter of 1.75 mm or 2.8 mm, respectively.

4.2.3 HDPE

Results from the study from Baechler et al. [35] show a proof of concept of turning recycled HDPE milk jugs into a 3D printed product (Figure 18). Their RecycleBot produced filament with a diameter ranging from 2.2 – 3.2 mm with 65% within the desired diametrical range and the density ranged from 0.437g/100mm to 0.694g/100mm of filament, largely caused by the variation in diameter.

The energy required to produce a meter of filament was found to be roughly 60 Wh, heating accounted for roughly two thirds and the motor energy use accounted for the other third. The energy required for the shredding process was found to be negligible [35].

Three issues were found. First, the filament production required some physical assistance to draw the filament from the extruder. Devices to automatically draw the filament failed, mainly due to the second issue related to an inconsistent rate of extrusion which is related to the third limitation,

Figure 18: HDPE milk jugs, cut into pieces [13].

namely the heterogeneous waste feedstock. So, using homogenous waste feedstock or large batch mixing after shredding will decrease these issues.

Extrusion was also affected by the size and type of shredded plastic. Thin, light pieces from milk jugs did not extrude well because it was not easily drawn into the heating section of the extruder. Heavier pieces from detergent containers performed much better. Using small pieces (< 5mm x 5mm) added to a better extrusion rate.

Some products were successfully 3D printed from the recycled HDPE filament; however the quality did not match the quality of products printed from commercially available virgin ABS on the same

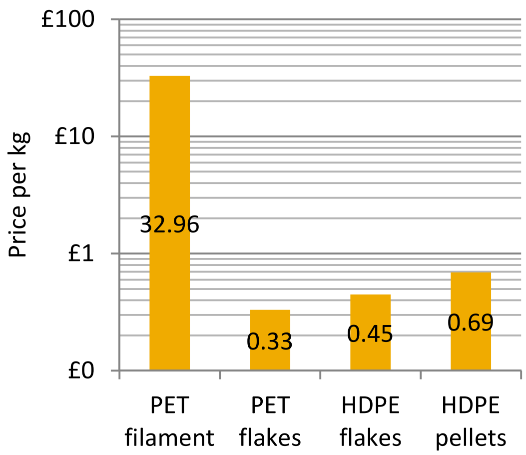


Figure 19: Average prices of PET 3D print filament, PET flakes, HDPE flakes and HDPE pellets for December 2015.

machine. The reasons for this difference can be attributed to i) thermal warping during printing makes HDPE harder to work with, ii) printing settings have been optimised for ABS and iii) the variation in diameter of the filament make it hard to print at a constant rate.

They believe that further experimentation and increased automation will continue to improve the quality of prints. Probably some progress has been made since the publication in 2013, however commercial available HDPE filament is still hard to find.

4.3 Time consumption

The process of turning plastic household packaging into a 3D printed product requires quite some time. The different processes are briefly discussed here.

To recycle a plastic household bottle, the bottle has to be washed, labels have to be removed and subsequently the bottle has to be cut in smaller pieces. These pieces have to be ground in smaller pieces. Baechler et al. quantified the time used for this whole process based on a HDPE bottle, however washing time was not included, because of large variance based on cleanliness. They used an office shredder for grinding. Shredding the material took roughly 10 minutes for 100 g [35]. Based on a mass of 5.85g/m for filament with a diameter of 2.8mm, this 100 g can produce roughly 17.1 m of filament.

The extrusion process consists of the start-up time and the actual extrusion time. The former was found to vary in between 25-45 minutes, depending on the electrical power supplied. The actual extrusion rate was found to be roughly 90mm/min for filament with a diameter of 2.8 mm [35].

4.4 Prices

In Figure 19 the prices of PET filament are compared with PET flakes. Prices of HDPE flakes and pellets HDPE are included as well for comparison. Data of the flakes and pellets are based on average offer prices[3]. Prices of the PET filament are based on average selling prices of four different suppliers (3x USA, 1x The Netherlands) varying between £14 and £51 per kg. The prices are converted to UK pounds[4] and shipping costs are excluded.

From Figure 19 can be seen that there is currently quite a gap between the price of raw materials and the filament. This suggests that the profit margin on currently sold filament is quite high, which

[3] http://plasticker.de/preise/preise_monat_single_en.php
[4] 0.735 GBP/EUR; 0.658 GBP/USD

might change when more suppliers enter the market, likely resulting in lower prices of filament.

Further it can be noticed that HDPE flakes sell at a lower price than the pellets due to extra process steps required to produce pellets.

4.5 Environmental impact

The decreasing costs of 3D printers allow for distributed low-cost production. This raises questions about the environmental impact of distributed manufacturing, which has been the topic of some recent studies [39, 40]. Kreiger et al. [40] carried out a preliminary Life Cycle Analysis (LCA) in order to evaluate the environmental impact of distributed polymer products compared with conventional manufacturing. The study evaluated three different products and two different materials: ABS and PLA with different internal fill percentages. Besides, they included electricity generated by photovoltaics (PV) as a scenario for distributed manufacturing and compared this with traditional electricity. Based on their findings they concluded that distributed manufacturing by an open-source RepRap 3D printer will have less environmental impact than conventional manufacturing for a fill composition less than 79%. Besides, the authors argue that the impact can be reduced further due to the ease of adapting to PV power and by recycling filament.

A similar study was carried out by Kreiger et al. [39] focusing on the LCA of recycled HDPE for 3D printing. They found that distributed recycling using the RecycleBot [35] uses less embodied energy compared with a best-case scenario for centralised recycling, based on Detroit, a high population density city.

4.6 Conclusions

PET bottles are already recycled into filament on a commercial scale. To produce high quality filament, the input material should be largely homogeneous. Producing filament from household plastics on a small scale using (open source) filament extruders is possible and can be cost-effective, but is quite time consuming.

HDPE bottles can be turned into filament as well; however this material proves more difficult to print, mainly due to the thermal properties of HDPE.

Refil Dodeca, a commercially available 3D printed lamp from recycled PET bottles. Image courtesy: Refil BV.

5 Plastic supply chain in London

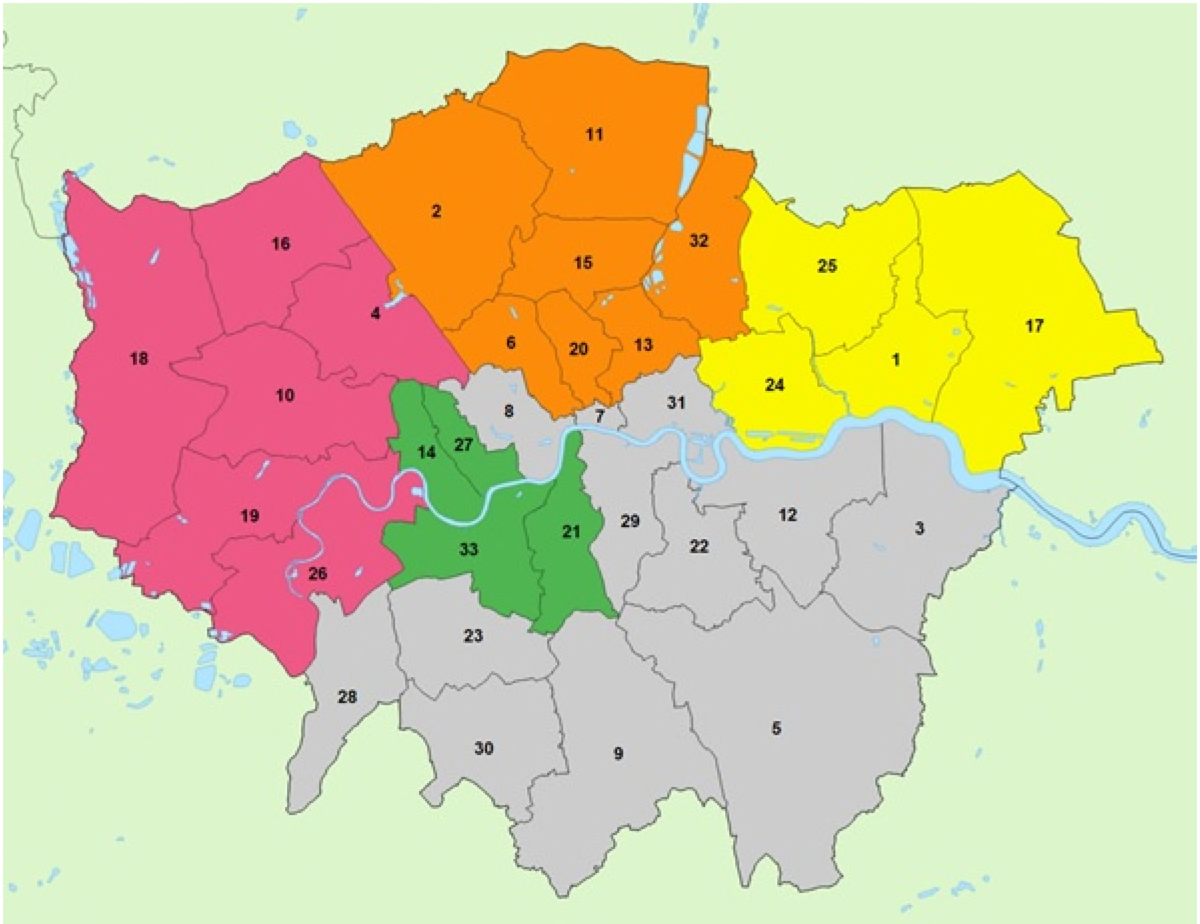
In this chapter the plastic supply chain in London will be analysed and the potential and costs of redistributing plastics will be evaluated. As found from the analysis in the previous chapters, PET and HDPE are the main plastics that are currently recycled. Since these materials are mainly found in packaging, the study will focus on the Local Authority Collected Waste (LACW).

5.1 Introduction

Greater London consists of 33 boroughs and has a number of waste disposal authorities. There are four joint waste authorities: East London, North London, West London and Western Riverside, each comprising some of the boroughs, as shown in

Figure 20. The other boroughs are independent waste authorities.

Large differences exist in the waste strategies and recycling rates among the boroughs, Figure 21 shows the latter for each borough.



1. Barking and Dagenham
2. Barnet
3. Bexley
4. Brent
5. Bromley
6. Camden
7. City of London
8. City of Westminster
9. Croydon
10. Ealing
11. Enfield
12. Greenwich
13. Hackney
14. Hammersmith and Fulham
15. Haringey
16. Harrow
17. Havering
18. Hillingdon
19. Hounslow
20. Islington
21. Lambeth
22. Lewisham
23. Merton
24. Newham
25. Redbridge
26. Richmond
27. Royal Borough of Kensington and Chelsea
28. Royal Borough of Kingston upon Thames
29. Southwark
30. Sutton
31. Tower Hamlets
32. Waltham Forest
33. Wandsworth

Figure 20: Waste disposal authorities in Greater London.

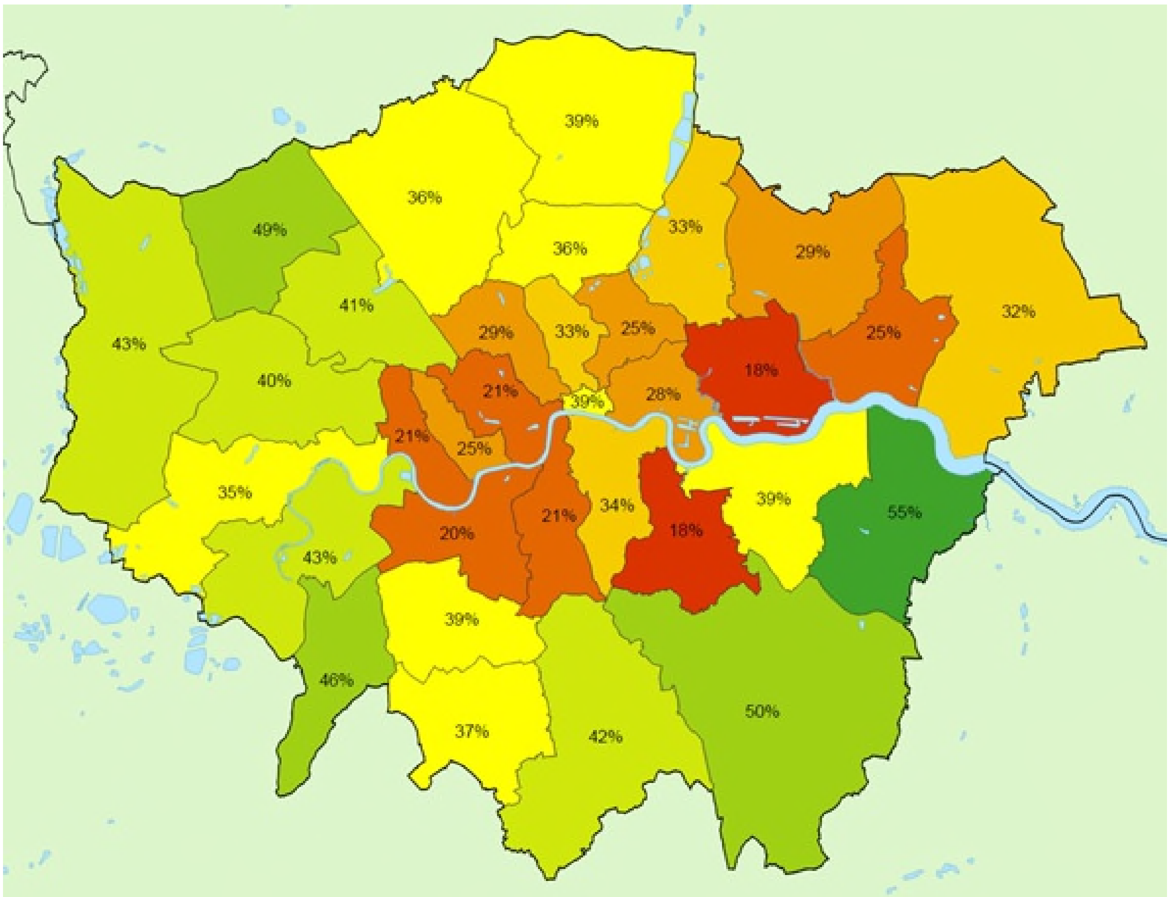


Figure 21: Overall recycling rates of the London boroughs from 2013/2014 [4].

5.2 Plastic waste

To get an idea about the current waste processing supply chains, waste statistics from WasteDataFlow are used. WasteDataFlow is the web based system for municipal waste data reporting by UK local authorities to government [41]. The dataset contains information about the collected waste and about the MRF and reclaiming facilities where materials are sent to for each London borough for each quarter of the year. The information about the waste streams is divided into different waste categories, such as plastic, paper and glass. One category is called 'mixed plastic bottles', but detailed information about the types of plastic is not provided and the majority of the waste authorities do not report this. Besides, a large part of the waste is inside the category of co-mingled materials which will include plastics as well. Since the quantities are provided per waste category for both collection and 'sent for recycling', the amount of plastics recovered from the co-mingled waste stream can be estimated. In Table 4 the data are shown for each London borough.

The total reported waste collected by all the authorities in London over 2014 amounts to roughly 4.2 Mtonnes, this is in the same order of magnitude as the 3.8 Mtonnes of total LACW collected in 2008, as described in section 2.3. For London in total 317 tonnes of mixed plastic bottles and 10,305 tonnes of plastics were collected in 2014, see Table 4.

Table 4: Input and output of plastic waste (tonnes) per London borough during 2014, data from WasteDataFlow [41]

	Input			Output		
borough	**mixed plastic bottles**	**plastics**	**total**	**mixed plastic bottles**	**plastics**	**total**
Barking and Dagenham	188.10	-	188.10	786.40	-	786.40
Barnet	2.66	7.53	10.19	2.66	2,596.60	2,599.26
Bexley	22.00	231.00	253.00	27.00	2,462.00	2,489.00
Brent	2.11	41.90	44.01	948.12	569.33	1,517.45
Bromley	15.95	-	15.95	1,271.14	412.54	1,683.68
Camden	-	8.98	8.98	-	2,014.47	2,014.47
City of London	-	-	-	-	78.22	78.22
Croydon	-	-	-	1.67	1,050.20	1,051.87
Ealing	72.47	455.85	528.32	69.16	3,038.88	3,108.04
East London Waste Authority	-	2,860.34	2,860.34	169.31	2,860.34	3,029.65
Enfield	-	-	-	-	-	-
Greenwich	-	138.44	138.44	-	3,511.83	3,511.83
Hackney	-	44.34	44.34	775.39	385.26	1,160.65
Hammersmith and Fulham	-	-	-	-	1,453.92	1,453.92
Haringey	-	8.13	8.13	908.38	19.16	927.54
Harrow	-	30.60	30.60	-	1,766.25	1,766.25
Havering	-	-	-	659.00	2,010.10	2,669.10
Hillingdon	-	158.83	158.83	-	1,279.82	1,279.82
Hounslow	-	80.00	80.00	-	2,638.00	2,638.00
Islington	-	2,262.24	2,262.24	-	2,660.33	2,660.33
Lambeth	-	73.48	73.48	-	1,481.33	1,481.33
Lewisham	-	31.28	31.28	1,703.60	83.80	1,787.40
Merton	1.42	6.97	8.39	158.63	281.67	440.30
Newham	7.25	231.47	238.72	534.43	1,547.06	2,081.49
North London Waste Authority	-	120.81	120.81	-	918.79	918.79
Royal Borough of Kensington and Chelsea	-	-	-	-	-	-
Royal Borough of Kingston upon Thames	-	1,222.40	1,222.40	-	1,222.70	1,222.70
Redbridge	-	-	-	-	2,573.49	2,573.49
Richmond upon Thames	-	1.30	1.30	1,116.83	14.19	1,131.02
Southwark	3.00	2,027.71	2,030.71	1.64	1,464.93	1,466.57
Sutton	-	5.88	5.88	991.67	918.74	1,910.41
Tower Hamlets	-	185.96	185.96	-	1,943.31	1,943.31
Waltham Forest	-	10.36	10.36	-	3,142.17	3,142.17
Wandsworth	1.74	49.70	51.44	1.40	2,034.96	2,036.36
West London Waste Authority	-	1.65	1.65	1,599.05	61.74	1,660.79
Western Riverside Waste Authority	-	-	-	-	609.81	609.81
Westminster City Council	-	7.36	7.36	15.47	7.36	22.83
Total	**317**	**10,305**	**10,621**	**11,741**	**49,113**	**60,854**

The total co-mingled household waste collected for recycling amounted to 469 ktonnes. For the same period, the amount sent for recycling is 11,741 and 49,113 tonnes of mixed plastic bottles and plastics, respectively. This indicates that majority of the recovered plastic bottles (97%) is part of the co-mingled waste stream and is sorted at the MRF. Of all the plastics, 21% is collected for recycling separately, the remaining 79% is recovered from the co-mingled waste stream sent for recycling.

Although no specific recycling rates for plastics in London are found, based on the estimated amount of 380,000 tonnes of plastics in London's LACW waste, the plastic recycling rate is only 16%.

5.2.1 Transportation of recycled plastics

Waste will be collected at kerbsides, civil amenity sites or other bring sites. The waste can be transported to a waste transfer station or to a MRF directly. At a waste transfer station general waste and recyclable materials are bulked up before being transported to a MRF for further treatment. After processing at a MRF, the plastic waste stream will be sent to a final destination for recycling.

Per borough, data are available for the names and postal codes of the MRFs and waste transfer stations used. Besides, for recyclable waste, the final destinations of the materials leaving the MRF and sent for recycling are given together with the amount of the waste. However, waste can travel from one MRF to another MRF for further processing, for example if the first MRF has not the capacity to process the waste at that specific moment. In this case, the recorded final destination is another MRF. This waste will still be transported at some stage from the latter MRF to another location, but the exact location is not known.

The postal codes of the MRFs, waste transfer stations (TS) and final destinations (FD) of recycled plastics have been mapped, see Figure 22. To get a better distinction, the final destinations which act as a MRF are excluded from the map. If a postal code of a final destination matches a postal code of a MRF or TS, the location is not regarded as a final destination. From now on, the final destination are facilities which are not recorded as a MRF or TS in the data file from the London boroughs, based on the postal codes. As can be seen, the locations of the MRFs are mainly concentrated in London, the same counts for the TSs. The FDs are more widely distributed over the UK and plastic waste from one borough has been sent outside the UK to a non-European destination.

At some of the FDs, the sorted plastic can be

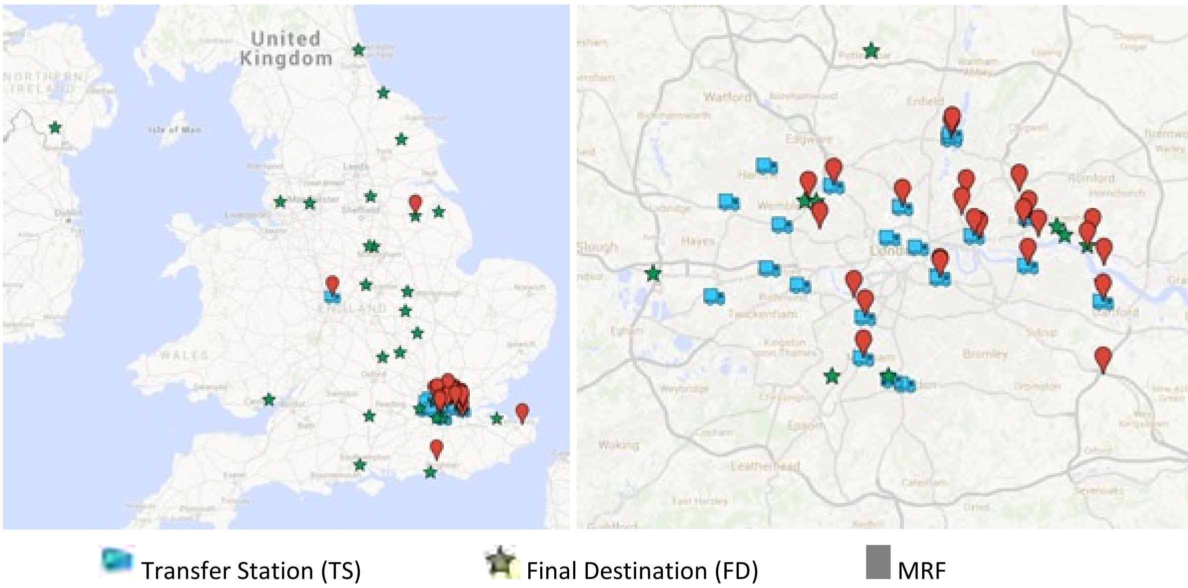


Figure 22: Locations of different entities in the plastic waste processing industry for waste collected in London during 2014 (left), the area for London is shown separately (right).

transported further, for example via rail. However, information about the further locations is not known. At other FDs the sorted plastic materials will be processed further into semi-finished products such as plastic flakes, pellets and fibres. Information about the further processing locations is not available; however, these products will be transported again to manufacturers of plastic products such as packaging. Other companies such as food suppliers will use this plastic packaging material to package their products which will be sold to the retail industry which will distribute the final products to their shops where customers will buy the product and will dispose it again after use. This shows that the locations depicted in Figure 22 represent just a small part of all the entities involved in the material supply chain of plastics used in London. Moreover, the supply chain of virgin plastics will add more locations to the total supply chain of plastics. This suggests that local plastic recycling can offer new ways to reduce the environmental impact caused by the transportation of plastics in the current plastic supply chain.

Of the total plastic waste of 60,854 tonnes, the exact destination of 7,790 tonnes (13%) is unknown. Of this amount, 99 tonnes are sent outside the UK to another European location and 334 tonnes are sent to a location outside the EU.

In order to get an estimation of the distances involved in the part of the waste distribution which is known, some assumptions have been made. Only the part of the waste is analysed for which the locations are known, this is 53,064 tonnes which corresponds to 87% of the total plastic waste. If waste travels from location A to B and B is a MRF or TS, then the final destination is based on the final destinations of the waste departing from location B. In this case, the total distance is the distance from A to B and from B to a FD (not being a MRF or TS). Since the locations to the FDs are different, there will be a minimum, average and maximum distance. Besides, waste from location A can come from the given MRFs or from TSs used by the MRFs. Since only the location of the TS is specified (if any) while information about the amount of waste is unknown, the additional distances from the TSs are excluded from this analysis. The minimum and maximum distances of the different MRFs used by a borough to the specified destination are calculated. The distances are obtained by the Google Maps Distance Matrix API. The distances between the provided postal codes are calculated based on the distance required by car.

In Figure 24 the minimum, maximum and average distances from the recycled plastic waste arising in London are shown.

Although the information is limited, one can see from Figure 24 that all the waste is sent to locations within a distance of 950 km. Based on the average distances, roughly 80% of the waste is sent to locations within 270 km. Assuming a distance of 70 km within (Greater) London itself, then 79% of the plastic waste is sent to locations within London, based on the minimal required distances. Based on the maximum required distances, this is 12% of the total plastic waste. The actual value is most likely somewhere in between; based on the average distances 24% of the total plastic waste is sent to locations within London.

Based on the calculated distances and the amount of plastic waste sent to the different locations, the CO_2 emissions are estimated. To determine these emissions, data from a study from WRAP are used [42]. They assume road transportation of plastic bottles by 40 foot containers containing 20 tonnes of plastic bottles. For a full truck load they assume 55.8 gCO_2/tonne-km; for an empty truck this amounts to 42.1 gCO_2/tkm. For simplicity it is assumed that each truck will be full to the final destination and will return the same distance empty, so a total of 97.9 gCO_2/tonne-km for a return trip. This is in the same order of magnitude as figures presented by a guidelines from Cefic [43], which assume total CO_2 emissions of 83 gCO2/tonne-km for a 40 tonne truck, based on a payload of 20 tonnes and 50% empty running. The results shown in Figure 23 are based on the minimum, maximum and average distances as discussed before.

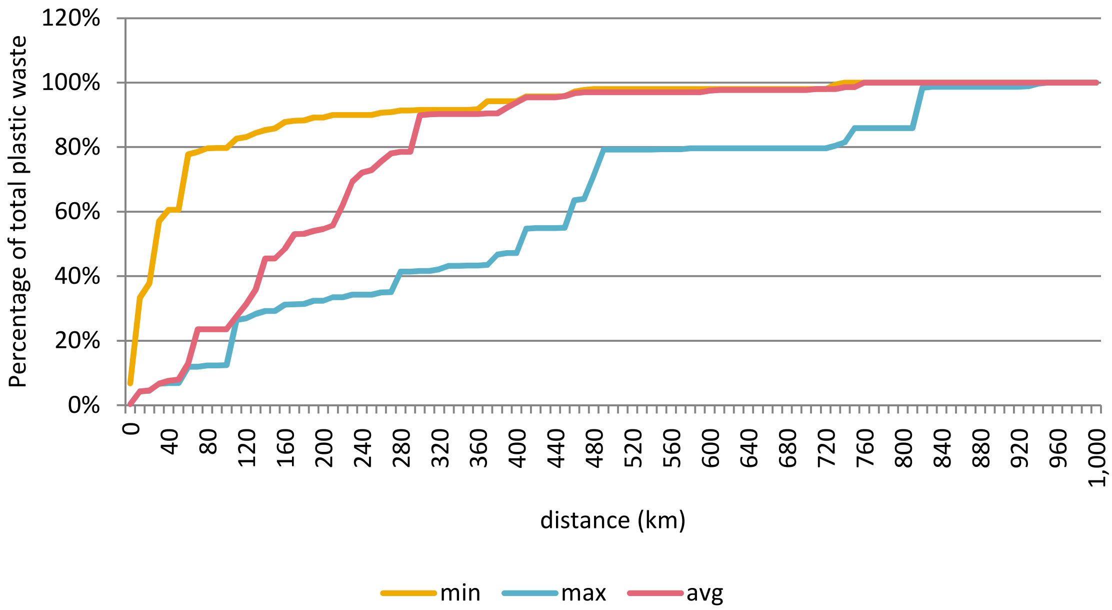


Figure 24: Distance from waste collection centre to final destination based on plastic waste from London boroughs over the year 2014.

From Figure 23 can be seen that the CO_2 emissions caused by the plastic waste transportation from the MRF centres to the final destinations amounts to roughly 900 tonnes. This is just a small fraction of the whole plastic waste supply chain, but gives an indication about the CO_2 reduction potential. To put this value into context, the total CO_2 emissions caused by the transport sector in London have been estimated to be 7.6 Mtonnes in 2013[5].

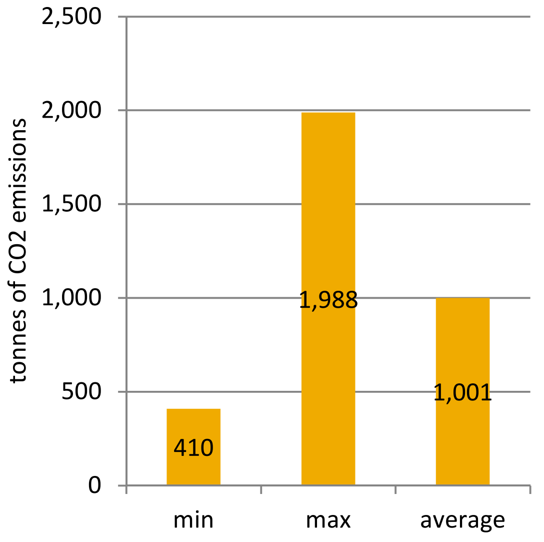


Figure 23: Tonnes of CO_2 emissions from the transportation of plastic waste from London on an annual basis

5.3 Conclusions

Overall recycling rates in London differ greatly per borough and the analysed data suggest that 97% of the recovered plastic bottles are within the co-mingled waste stream and sorted out at Material Recovery Facilities. Although no specific recycling rates for plastics in London are found, based on the estimated amount of 380.000 tonnes of plastics in London's Local Authority Collected Waste, the plastic recycling rate is only 16%. Based on the analysis of the locations of the plastic reprocessors, an estimation has been made about the share of the recycled plastic waste currently processed in London. Due to a lack of data on the exact waste flows among the waste processing locations, exact figures are found hard to obtain. Based on some assumptions a range of distances has been obtained. On average roughly a quarter of the plastic waste is sent to locations within the area of London.

6 Other materials

This study has mainly been focused on plastic materials, however other materials can be used for additive manufacturing as well. Metals are already widely used, besides a range of other materials are applied or explored for AM. This chapter will briefly analyse the potential of redistributing metal materials for AM. Besides, some other materials will be described.

6.1 Metals

6.1.1 3D printing

The techniques applied for metal 3D printing are mainly Directed Energy Deposition (DED) and Powder Bed Fusion (PBF). With DED it is possible to add melted material onto a specific surface. The material, which can be deposited from any angle due to 4 and 5 axis machines, is melted upon deposition with a laser or electron beam. For DED metals in the form of a powder or wire is used. As the term already implies, for PBF metals in the form of a powder are used.

For a powder the grain size and the shape of the powder are important for the quality of the finished product. Small round grains give the best results.

The DED process is a cold process, in the sense that the operating chamber is cold, this is in contrast to PBF. Although the same metal powders can be used, in the DED process the unused material can be recycled for the following DED process. In the powder bed fusion process, all the powder in the operating chamber gets affected by the temperature and cannot be directly reused for the same process.

Metal printers can produce industrial grade products, which opens new opportunities for more functional products compared with plastics. However, compared with 3D printers for plastics, the metal printers require professional skills in design and operating. Besides, metal printers are significantly more expensive, so highly distributed manufacturing is less likely; nonetheless, first steps have already been made with the development of an open-source metal 3D printer [44]. The differences in value and applications of the products could offer possibilities to redistribute manufacturing of metal products, although this might become less distributed as with plastics because of the aforementioned factors.

6.1.2 Waste in London

Similar to the approach discussed in section 5.2 for plastics, the metal waste in London has been analysed. In total 84,699 tonnes of metals have been collected and sent for recycling in London in 2014 [41]. For 62,652 tonnes (74%) of the total waste the destination of the sorted waste is known, see Table 5.

Table 5: Composition of metal waste in tonnage for London in 2014

Metal category	Known destination	Unknown destination	Total
Aerosol cans	-	57	57
Aluminium cans	2,044	84	2,128
Aluminium foil	-	73	73
Bicycles	1	7	8
Fire extinguishers	-	1	1
Gas bottles	63	33	96
Metals from Incinerator Bottom Ash	24,413	12,210	36,624
Mixed cans	16,713	4,655	21,368
Other Scrap metal	16,238	4,240	20,478
Steel cans	3,179	687	3,866
Total	**62,652**	**22,048**	**84,699**

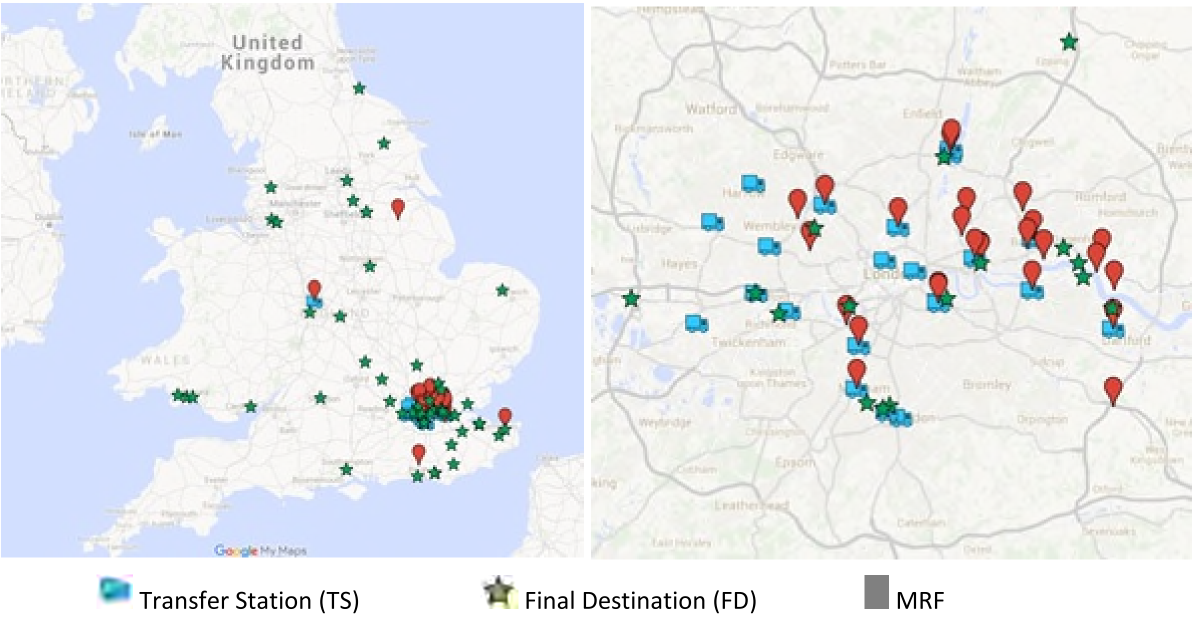


Figure 25: Locations of different entities in the metal waste processing industry for waste collected in London during 2014 (left), the area for London is shown separately (right).

The locations of the entities involved in the metal waste recycling from the metal waste arising in London have been mapped in Figure 25. Compared with plastics, the locations of the metal processing plants are closer to London.

In Figure 26 the minimum, maximum and average distances from the MRFs to the FDs are shown. As can be seen, on average 21% of the metal waste is transported to locations within London, assuming the locations within a travel distance of 70 km as part of London. Based on the minimum and maximum distances, this is in the range of 18-48%. Comparing Figure 24 with Figure 26 shows that the proportion of metal recycling within the London area is slightly lower than the amount of plastics recycling.

6.2 Bio based materials

Plastics made from starch-based materials offer the opportunity to use local feedstock as raw materials. Thermoplastic starch can be reinforced

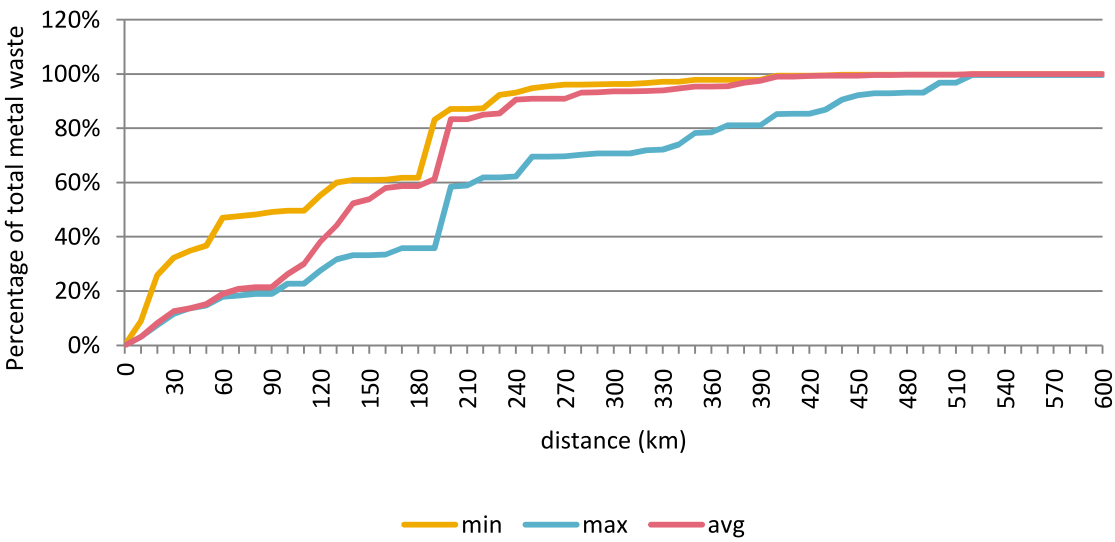


Figure 26: Distance from waste collection centre to final destination based on metal waste from London boroughs over the year 2014.

by natural fibres to get the desired properties while remaining biodegradable. Brett et al. [45] studied an epoxy-based ink that enables 3D printing of cellular composites, creating fibre-reinforced composite architectures similar to wood.

6.3 Polymer composites

Recently, 3D printing filaments consisting of polymer composites have entered the market. For example, PLA mixed with (recycled) wood fibres (i.e. fillers) enables to 3D print objects with a wood-like appearance, see Figure 27. PLA mixed with metals, such as copper or bronze, are available as well. A torso printed with a bronze filled filament gives the object a look similar to a traditional bronze sculpture, see Figure 27. Filaments filled with other materials, such as bamboo, cork and carbon, exist as well.

The filled filaments offer ways to produce products which look, feel and behave differently. This opens a wide area of possible new products and could offer new ways to integrate local materials, such as saw dust as wood fibres. However, from a recycling point of view, these polymer composites will create an extra barrier to sort and separate the materials of the product's end of life.

6.4 Conclusions

Metals are widely used in 3D printers, however the cost of suitable 3D printers in combination with the skills required to print metal products are a limiting factor for highly distributed manufacturing. Open-source metal printers - currently in a research phase - could pave the way for more low-cost alternatives.

A brief examination of the metal waste arising in London shows that roughly 85 ktonnes of metal waste has been collected for recycling in 2014. On average 21% of the metal waste is transported to locations within London, assuming the locations within a travel distance of 70 km as part of London. This is in the same order of magnitude to the figures found for plastics.

Other materials which could enable the use of more local materials are bioplastics (e.g. PLA) made from renewable sources such as starch.

More recently, filaments formed by the mixing of thermoplastics with other materials such as wood, copper and bronze creating polymer composites which offers new ways to produce products with another look, feel and material properties. However, by mixing various materials this would complicate the recycling process even further.

Figure 27: 3D printed shape of an elephant with PLA-wood (left) and a torso printed with PLA-bronze (right), both shown in the iMakr store in London.

7 Business scenarios

In this chapter some scenarios for new business models around 3D printing will be discussed in relation to the possible effects on the distribution of material supply chain.

7.1 Introduction

The benefits of the economies of scale have driven large-scale manufacturing which in turn has relocated manufacturing to low-labour cost countries in order to further reduce production costs [40]. Additive manufacturing could change this, because labour costs could represent a smaller fraction of the production costs, depending on the required skills to operate the 3D printer.

On an abstract level, most processes involved to produce a product remain the same for 3D printed products. There is still a need for raw materials, manufacturing and for the distribution of materials and products. In Figure 28 a schematic diagram of a 3D printed product system is shown. Starting with material collection in which the materials from post-consumer products are collected and sorted. Next, the materials are pre-processed before they can be used to produce 3D print material such as filament or powder. Subsequently, from the 3D print material a 3D model can be printed by a 3D printer. After some post processing steps, the final product is ready. The product can be used by a consumer before it could return to the material collection.

All these processes can be carried out by the final consumer in a closed system if the consumer has the right materials and equipment. In contrast, each process can be carried out by different

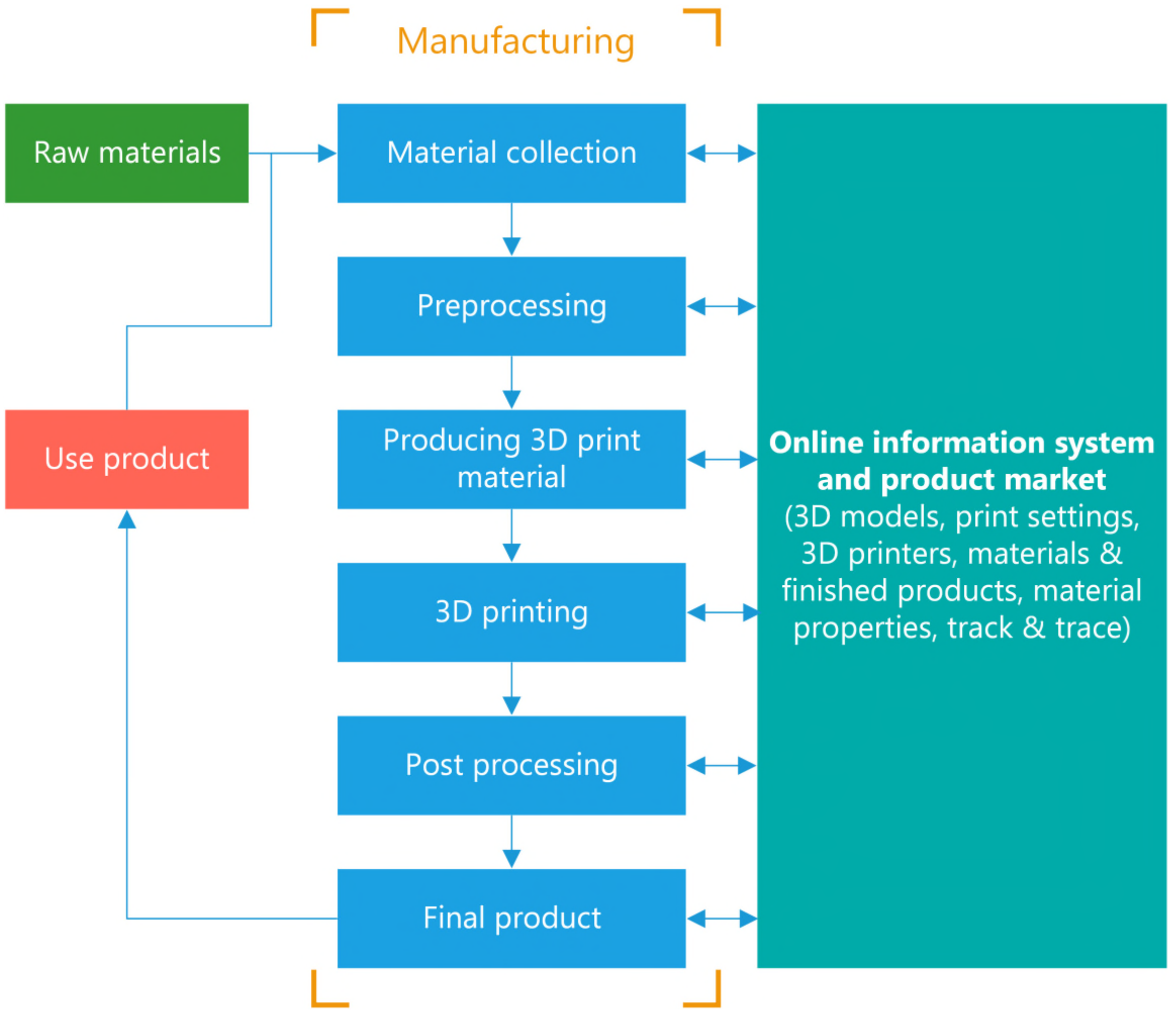


Figure 28: Schematic diagram of a 3D printed product system

entities in which each entity can sell its (semi-finished) product, such as raw materials, filament or 3D printed products.

An online information system will support sharing of these (semi-finished) products acting as a virtual market place. The online system allows finding the nearest location of the required supplies or suitable 3D printers. Besides, the online information system can provide tips & tricks based on user experiences related to filament extrusion or 3D printing, such as optimal printing settings for certain materials. A digital product design can be made by the user or can be obtained online. All these processes offer opportunities for new services.

The distribution of the physical materials and (semi-finished) products depends on the number of entities involved in the whole process. The distribution of materials is one of the key areas to be evaluated in this study. Some of the questions are: How can 3D printers change the distribution of materials and products? What are the key drivers behind the current scenario and possible future scenarios? Which conditions are required to get a more distributed material supply? Which new business models can be developed?

7.2 Scenarios

In order to study the potential impact of redistribution of materials through 3D printers, two scenarios will be described based on filament producers from recycled material.

7.2.1 Scenario 1: existing supply chain + new players

In the current scenario the filament producers using recycled materials are added to the current 3D printing landscape with minor effects on the current business models of other entities in the supply chain.

The filament producers are just new entrants to an existing market and supply filaments like other filament producers with the difference that they use recycled material. The recycled filament producers operate mainly centralized, see Figure 29 for a schematic representation.

The smaller circles represent smaller entities, which can be a single household or a small business company. Some of these smaller entities – the early adopters - do have a 3D printer, but use this mainly for own use and buy their filament via the existing market.

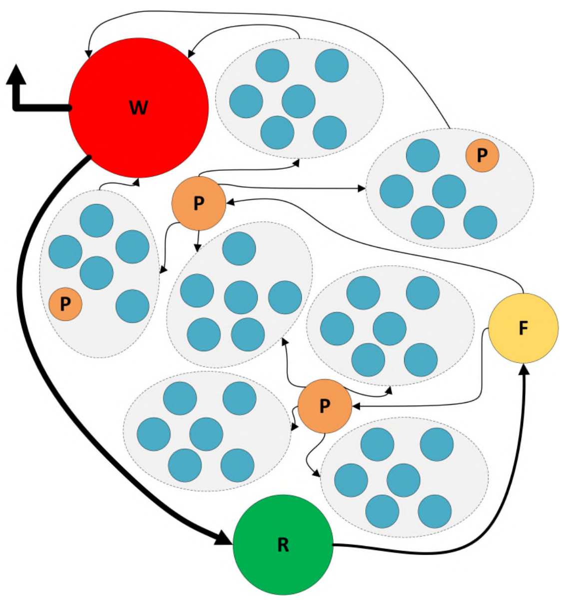


Figure 29: Current scenario with a central filament producer (F), a central waste collection site (W), a waste recycling centre (R) and some distributed 3D printers (P). The circles in the grey ellipses represent individual entities. Blue circles are small entities which mainly act as consumers; small entities with a 3D printer are indicated with a (P).

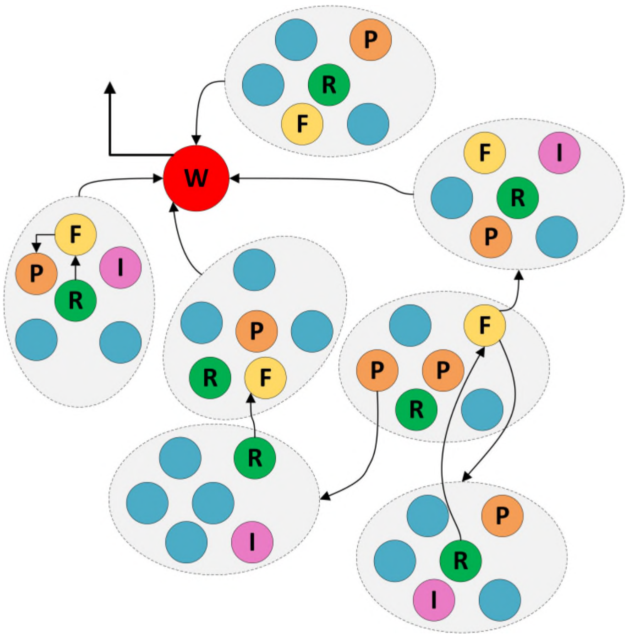


Figure 30: Redistributed material supply chain.

7.2.2 Scenario 2: redistributing supply chains

In this scenario, the recycled filament producers will be more distributed. More entities have a 3D printer (P), some recycle and sell the sorted materials (R), others produce filament from recycled material (F) and some early adopters are independent by having an integrated production system which includes a filament maker and a 3D printer (I).

When 3D printers become more common, more interaction between different users takes place. Since more users are involved, the demand for information exchange about locally available materials might increase. A more advanced information system may include information about local available 3D printers paving the way for cloud manufacturing [46].

Distributed manufacturing may decrease the transportation of materials and products over long distances, but will increase the logistics at the local level. This could create opportunities for local delivery services of goods.

The increasing affordability of 3D printers will lead to an increase in competition, from SMEs and individual entrepreneurs, but also from home fabrication by so-called ‘prosumers’. When 3D printers become more affordable, value creation increases, but it can become more difficult to capture this value, since competitors can easily adapt their business strategies to the changing market conditions. Therefore it is likely that the competition among businesses will increase [47].

It will partly depend on the efficiency of small scale production systems for 3D print materials to become more locally produced. If this will be the case, existing large manufacturing companies may start to distribute their production capacity. A manufacturer of custom-made plastic toys may be an early adopter of such a transition.

7.3 Conclusions

As 3D printers become more commonly available, it is likely that the exchange of materials, products and information related to 3D printers will increase. Business models can evolve around the various processes in the production supply chain, from raw material and 3D model suppliers to manufactures of complex 3D printed parts.

As products become increasingly locally manufactured, the local distribution of goods will intensify. Since the production could take place at the nearest suitable 3D printer having printing capacity, the delivery of 3D printed products could become similar to the delivery of pizza’s, although the former might not be warm anymore. Anyway, it offers another area for new businesses.

This will lead to more value creation, but this may also make it more difficult to capture value.

8 Opportunities and challenges

In this chapter the opportunities and challenges for redistributing material supply chains for 3D printing will be discussed. The introduction will describe some of the factors which play a role in the distribution of materials and 3D printers. The rest of the chapter will be based on findings from the stakeholder survey on the barriers for using local materials for 3D printing.

8.1 Introduction

Opportunities and challenges regarding 3D printing and the related material supply can be associated with different aspects, such as technological, economic, environmental, regulatory, and behavioural. First general factors which influence the distribution of materials and 3D printers are discussed. Subsequently some barriers will be presented which are based on the results of a workshop organised around this theme. The chapter ends with some opportunities and finally the conclusions will be presented.

8.1.1 Factors influencing material distribution

Although it is hard to say how 3D print businesses will develop, it is clear that the distribution of materials depends on a number of factors such as the cost difference between raw materials and recycled materials and transportation costs.

The pricing of raw materials depends on the demand and supply of global markets. Since the world population is expected to grow and the share of the population which can afford modern products will grow at the same time, it is expected that prices of most raw materials will increase in the long term. The increasing prices of the finite raw materials combined with governmental regulations to decrease the amount of waste (e.g. cost of landfill) and improve recycling rates will likely result in better recycling technologies and therefore cheaper recyclable materials.

Next to the improved recycling techniques, increased material prices will probably influence the way materials are separated and collected. Besides, when materials become more expensive, manufacturers have an extra motivation to design products which are easier to disassemble.

Local manufacturing can decrease the need for transportation. One of the main drivers for businesses to shift from central to local manufacturing will depend on the trade-off between transportation costs and potential negative side-effects of distributed manufacturing related to economies of scale.

Since the amount of material required for 3D printed products is relative small, businesses could sell smaller quantities of materials. For a filament maker ten identical plastic bottles would probably have a higher value than a large bale of mixed bottles, because the latter requires more sorting and produces extra waste. Since it is more likely to find smaller quantities of specific materials locally, information about the location, amount and material properties can become more important in order to be able to obtain these materials on a distributed basis.

For more advanced materials, recycling can become harder, since the exact procedure to produce the materials may be undisclosed or may require more expensive techniques which are hard to achieve at a cost-effective manner at a small scale. On the other hand, materials may become more open source as well, which might increase the distribution of these materials.

A key question remains: At which scale does the recycling of certain types of waste become feasible? On which factors does this depend and what has to be changed or developed in order to make local recycling viable?

8.1.2 Smart local material networks

Since the information around materials becomes more important, IT services could be developed to track and trace materials. Knowing which materials are locally available will support the distribution of these materials. In this way, local materials might become part of a smart material network in analogy with a smart energy network.

In the future, organic printed RFID tags could be part of a solution to trace materials. Since speed is an important factor for this process, the number of manufacturing steps and the required number of different materials should be decreased to simplify and accelerate the production process of those tags [48]. Products tags could include information about the materials used inside and instructions how to disassemble or recycle the product at its end of life. A similar idea is known as a 'product passport' [49, 50].

For complex 3D printed products, combining different materials in an internal structure may become very hard to recycle. Lacking information about the exact material properties inside a product may cause these products getting landfilled in the end. Attaching the information about the 3D model data to the product may help to overcome this. Maybe this could even offer possibilities to develop a device which is able to reverse the 3D printing process by recovering the product's materials layer by layer to achieve proper separation.

Tags added to products will increase the production cost and could create an extra source of contamination during the recycling process. This is something to take into account.

8.1.3 Factors influencing the distribution of 3D printers

Obviously, the redistribution of materials through 3D printing depends on the distribution of 3D printers. If there are more 3D printers, the demand for 3D print materials increases and the related business opportunities will grow.

Some factors which influence the distribution of 3D printers are: the capital cost of 3D printers; the cost of use (cost of materials, energy demand); the ease of use / the required skills; printing time; the type of products which can be produced with 3D printers (e.g. functional or decorative products); the functional value of the printed products; the price difference between a 3D printed product and a similar product produced with traditional manufacturing; the presence of skilled people; the availability of materials.

8.1.4 Usability

A study by Ludwig et al. [51] shows that one of the main barriers for 3D printing to become a widely used technology is that the roots of failures are a complex problem area. According to their study, these failures can be related to three different levels: (1) device related (e.g. print settings), (2) socio-material (e.g. characteristics of the printer's location) and (3) task-related (e.g. problems with the tools used to build or prepare prints). Even for experts this is hard to master. They argue that playful approaches towards the use of 3D printers may help to learn how to operate the machines. So, applying 3D printers for educational purposes could help to overcome this barrier in the long run. As an example, 3D printed objects are already used in such a context with the so-called Minifig Battlefields[6]. Custom-made 3D printed LEGO objects are used to educate about WWI in a playful way. Potentially, this could be combined with actual 3D printers in the classroom to design and print your own models.

A study by Weller et al. [52] confirms that one of the limitations is that skilled labour and strong experience is required. To help to overcome this issue, Ludwig et al. argue that the software and hardware tools have to be improved in order to achieve a broad appropriation of 3D printers [51].

8.2 Barriers for using local materials

As part of the project a workshop has been organised, a summary about this workshop can be found in Appendix A – Workshop. Participants were asked to fill in a survey on the barriers to using local materials for 3D printing. The survey can be found in Appendix B – Survey. The barriers could be related to five predefined categories: (1) technological, (2) economic, (3) social/cultural/behavioural, (4) organisational and (5) regulatory.

In Table 6 the amount of surveys grouped by the working area of the respondents is shown.

[6] http://www.minifigbattlefields.com/education/

Table 6: Amount of surveys grouped by the working area of the respondents

Working area	No. of surveys
Academic - Design	3
Academic - Engineering	9
Academic - Business	6
Academic - Others	3
Industry	3
Total	**24**

In Figure 31 an overview of the survey results are shown. The "Total barriers" shows the total number of barriers mentioned by all the respondents. Not every respondent marked the severity of the barrier, so the amount of the identified barriers with a severity classification is shown separately. The number of barriers classified as "high" severity is shown per barrier category. Next, the number of barriers of which the likelihood to overcome is believed to be "never" is shown. The last column represents the total number of top barriers named by the participants per barrier category.

As can be seen, technological and economic barriers are mentioned the most, which could be related to the respondents' background and to the order in which the categories were presented. However, compared with the other categories, the largest amount of barriers classified as "high" severity is related to technological barriers. At the same time, they are almost all believed to be able to overcome within 30 years.

Figure 32 shows another representation of all the barriers grouped by severity and likelihood to overcome per category. To be able to include the likelihood category 'never' in the figure, this category has been converted to 50 years. The area of the bubbles represents the number of barriers.

From the figure it can be seen that for a large number of barriers the severity and likelihood are unknown. Furthermore, most barriers are regarded likely to be overcome in 3-4 years and are in the range of medium to high severity.

Since the workshop was centred around the production of plastic filaments and 3D printed products from plastic waste sources, although not explicitly asked, most respondents related the barriers to issues with the current plastic waste recycling into filament and to 3D printed products produced with the material extrusion technique.

For each barrier category, a short summary of the top barriers is presented below.

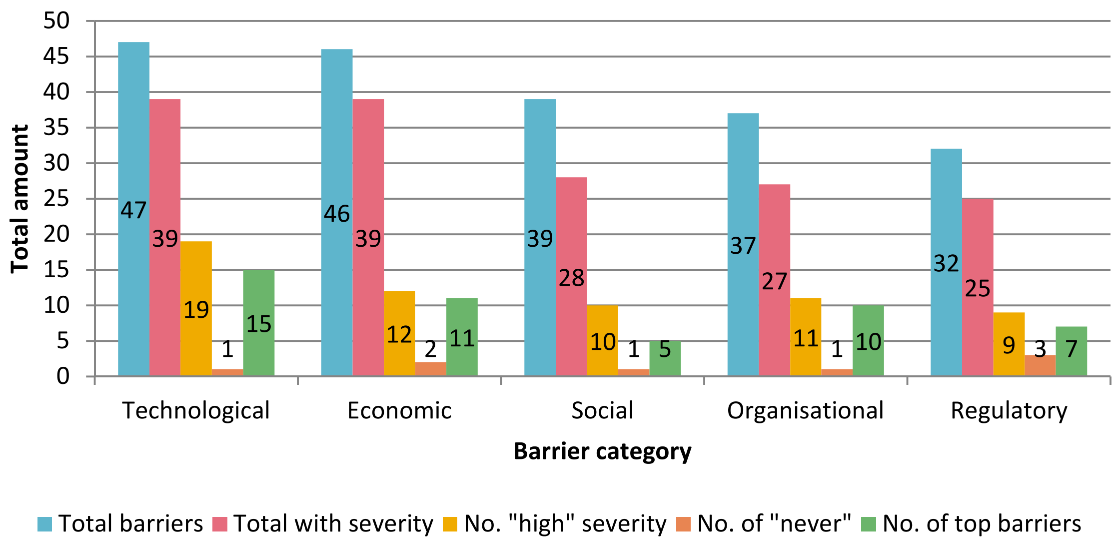


Figure 31: Overview of the survey results

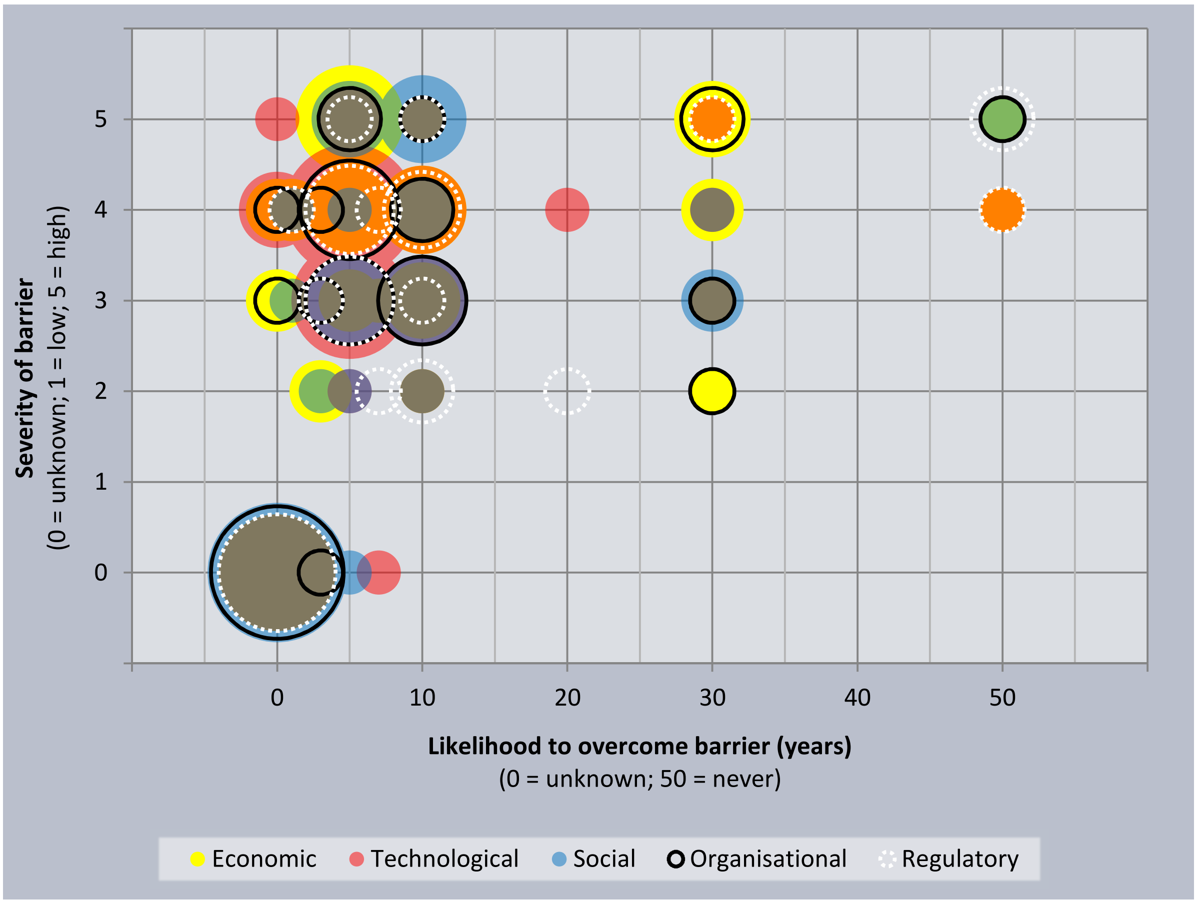


Figure 32: Overview of the barriers grouped by severity and likelihood to overcome per category

8.2.1 Top barriers

Related to technological barriers, the barriers considered as most important are related to the general lack of materials which are suitable to be recycled in order to be used in 3D printing. Besides, the availability of local materials is seen as a main barrier. A number of respondents identified top barriers to be the cost of small-scale sorting/recycling equipment and the less efficient processes at this scale. Besides, the availability or absence of machines suitable for small-scale recycling is regarded as an important barrier. Also the quality of the finished product (e.g. filament, powder or 3DP product) is considered a large issue which is linked to the lack of a quality-assured material supply. Another important barrier relates to the current state of the technology, which is perceived not suitable for mass production, which limits the applications and therefore the demand for local materials. Lastly, local skills and the awareness about 3D printing capabilities and limitations are seen as main barriers for more distributed 3D printer assisted manufacturing. Although the latter could be perceived as a social/educational barrier, it is also related to the current state of the technology which requires high level of skills.

The top economic barriers are related to the current consumer demand for 3D printed products and the cost of 3D printed vs. traditional manufactured products. Besides, the price difference of virgin and recycled materials, especially related to plastics with current low oil prices, is considered to be a high barrier. The cost of recycled material is also related to the economy of scale required to recycle materials. Recycling processes become more efficient at a larger scale, which favours centralised recycling facilities. Besides, the current market demands a certain volume of recycled materials, which is another driver for large-scale recycling processes. Since recycled plastic is a commodity, it competes with international prices and a strong pound favours imports of recycled material. Another barrier is related to the PRN/PERN (Packaging Recovery Notes/Packaging Export Recovery Notes) regulations, which stimulates exports of recycled material. Finally, the start-up cost for equipment is regarded as a top economic barrier; especially as the 3D-print industry is in its early stages and is constantly being improved (i.e. investment in today's tech could be rendered obsolete, fairly quickly).

The most important social barriers are associated with the lack of the acceptance/need to use recycled over virgin materials. This links to the poor recycling rates amongst consumers, who should become more aware of the value of the materials inside their waste. Lack of education about this topic is seen as a main barrier. Another barrier is related to the question of how playful experimentation can be moved into commercial products, or how to scale up.

Organisational barriers which are classified as important are related to the lack of open data & hardware for knowledge and skill sharing in- and outside companies. However, existing 3DP firms have the desire to have proprietary materials on which they can make revenues. Information about the local materials is mentioned as another main barrier, which adds to the difficulty to coordinate small-scale sources of waste. The lack of (distributed) circular business models and players in the value chain to organise local materials recycling is regarded as another important barrier. This relates to the lack of coordination across the business chain to reduce risk and increase stability in supply and quality of materials.

Local legislation and regulations regarding the use of materials (e.g. REACH) are considered important barriers to use locally sources materials. Besides, health & safety regulations and thorough tests of materials and 3D printed products and processes are needed. Furthermore, the government could develop regulations to enforce the use of recycled materials more.

8.2.2 Overview

All the mentioned barriers have been grouped per common theme in order to get an idea of the themes which are widely seen as a barrier to using

Table 7: Barriers grouped per theme

Barrier theme	No. of barriers	No. of top barriers
Current technology limitations (e.g. quality and cost of 3DP products)	33	9
Standards & testing, also related to trust and health & safety of products and processes	25	6
Limited (cost/efficiency/availability) small scale recycling/production systems	21	7
Behaviour/knowledge/trust/education/R&D regarding recycling and value of materials	18	3
Knowledge and skills regarding 3D printing	17	3
Cost of recycling, inefficient sorting and collection of waste	15	3
Laws enforcing/rewarding recycling	15	3
Economies of scale	14	3
Local limitations (skills, materials, money, legislation)	12	2
Economic drivers, focusing on low cost/high profit only	11	1
Innovative business models (circular economy, scale up)	11	5
Commodity market (price of virgin materials, price fluctuations, exports/imports)	11	4
Lack of collaboration in value chain	7	2
Legislation recycling/reuse	6	1
Lack of monitoring data material recycling supply chain	6	2
IP regulations limiting knowledge sharing / innovation	5	1
Innovative materials	4	2
Understanding of distributed manufacturing systems	3	0

local materials for 3D printing. Since some barriers could be associated with more themes, some are counted double. The results are shown in .

From the table it can be observed that current technology limitations and the lack of standardisation is mentioned most often as a barrier to using more locally sourced materials for 3D printing. Besides, the limited availability and efficiency of small-scale recycling technologies is another often stated barrier. Furthermore, it is interesting to note the perceived obstacles stemming from IP regulations on proprietary materials which limit knowledge sharing.

8.3 Opportunities for future actions

It seems that greater awareness & incentives are needed to recycle more materials; this could support the availability of local materials. 3D printing could provide the motivation for consumers to recycle more of the household waste.

New materials which are easy to regenerate could offer opportunities, so this is worth further research. At the same time, attention should be paid to the mixing of various materials in the waste stream, which could have negative effects on the overall recycling efficiency, such as the mixing of PLA with PET.

One area which could be explored is to use fewer pre-processing steps to recycle materials, for instance using raw material direct into 3D printing instead of converting it to filament first.

From the identified barriers it became apparent that there is a need for standardisation / certification of information, materials, hardware, processes and products in order to get better quality and safety assured products. This would help to promote inter-changeability and credibility around the use of local materials and 3D printed products.

There needs to be a better understanding of the economy of scale and how this influences the distribution of materials. Which constraints exist? Which materials are suitable? Which niches exist?

Knowledge and skill sharing covering the whole spectrum from material recycling, filament making, 3D print settings and the suitability of materials could foster the creativity and help to enter the market. The current lack of a structured way to organise these data offers opportunities to create such a platform or institution to cover these aspects.

8.4 Conclusions

Most barriers to using local material supply for 3D printing are related to technological or economic aspects. The lack of standardization and quality control is found to be a main barrier to use locally recycled materials, which needs due attention. Besides, the lack of skills and knowledge about 3D printing in general and on a local scale specifically is seen an important barrier. An open-source information sharing platform could support ways to overcome this barrier. Also, the economics of scale currently involved in the (plastics) recycling industry limits the use of local materials; smaller quantities are often costlier and less efficient to recycle. Further research in the area of the economics of scale involved in the material supply and how this influences the opportunities for a more local distribution of materials is recommended.

9 Conclusions

In this chapter the conclusions will be presented. First the key observations and considerations will be discussed, followed by the key challenges. Finally, the recommendations will be presented.

9.1 Key observations and deliberations

Additive manufacturing (AM) or 3D printing covers a wide range of technologies with varying functionalities, applications and product qualities. For this study the focus has been mainly on material extrusion processes, also known as fused deposition modelling (FDM), which uses thermoplastics to produce objects. This technology has been selected since it is the most distributed AM technology due to its lower capital cost compared with other AM technologies and since the technology offers opportunities to recycle materials which are widely available on a local scale.

From the waste perspective, plastics are of particular interest to be used as locally recycled material. Plastic recycling rates are still low and the low value density of the material causes higher transportation costs compared with other materials. From a distributed material perspective, plastics are highly distributed already, producing steady waste flows, since they can be found in many common products.

The key findings are divided into three categories: general observations, London case study, and business models.

9.1.1 General observations on 3D printing and its material supply

- Due to current limitations, 3D printing is still mainly used for prototyping and scale modelling, however there are indications that this will shift more towards the production of (final) products in the near future. This will open opportunities to distribute manufacturing.
- The material supply for 3D printing is mainly dominated by a few global suppliers which is related to the current low demand for these materials. Further, the volume of material required to print objects is relative small which add to the low demand.
- Due to this low demand, the price of 3D printing filament is relatively high. This acts as a stimulus to recycle material locally to produce your own filament.
- Recycling of household plastics such as PET and HDPE bottles into filament is possible and some small scale machinery such as grinders and extruders are commercially available.
- Distributed recycling using open-source equipment, such as the RecycleBot, uses less embodied energy than centralised recycling and can be cost-effective if compared to retail prices of printable household products, however the time consumption has not been included in the costs.
- The properties of PET are suitable for 3D printing; HDPE proofs more difficult to use due to its thermal properties.
- Using homogenous material (e.g. identical bottles) as input to produce filament results in the best quality.

9.1.2 The London case study

- A total of 291 3D printers and 2,165 makers exist in London, based on this figures it is currently (November 2015) the most popular city in Europe and the third in the world.
- London produces about 20 million tonnes of waste annually, of which about 20% comes from municipal waste. About 50% of this total waste is still sent to landfill. A yearly amount of roughly 380,000 tonnes of plastic waste arises in the municipal waste stream of London.
- The plastics PET and HDPE are already largely recycled and huge quantities exist in the household waste stream, mainly in the form of plastic bottles. There is a strong market for recycled plastic bottles, but decreasing oil prices may impact the plastic recycling market, since the price difference with virgin plastics becomes smaller.
- About 45% - 52% of the plastic bottles are collected for recycling in the UK, suggesting that a large amount of plastic bottles is still hard to sort out from the waste streams.

- Overall recycling rates in London differ greatly per borough and the analysed data suggest that 97% of the recovered plastics from municipal waste are within the co-mingled waste stream and sorted out at Material Recovery Facilities (MRFs). The plastics recycling rate is rather low, estimated to be only 16%.
- Plastics are sorted by type at MRFs and are baled and sent to reprocessing locations. A rough estimation shows that on average, roughly a quarter of the recyclable plastics waste is sent to locations within the area of London, assuming the locations within a travel distance of 70 km as part of London.
- Plastic PET bottles sorted, cleaned and turned into flakes. The yield of this process varies between 45 - 75%; losses are due to contamination of the baled PET bottles, such as metal cans, residual liquids inside bottles, glue, caps and labels.
- A brief examination of the metal waste arising in London's municipal waste stream shows that roughly 85 ktonnes of metal waste has been collected for recycling in 2014. On average 21% of the metal waste is transported to locations within London.

9.1.3 Deliberations on business models and supply chains

- As 3D printers become more commonly available, it is likely that the exchange of materials, products and information related to 3D printers will increase. Business models can evolve around the various processes in the production supply chain, from raw material and 3D model suppliers to manufactures of complex 3D printed parts.
- As products become increasingly locally manufactured, the local distribution of goods will intensify. Since the production could take place at the nearest suitable 3D printer having printing capacity, this could offer opportunities for automation software determining the optimal print location.

9.2 Key challenges

The key challenges found for distributing material supply chains for 3D printing are presented below.

- The low quality of the 3D printed products printed with material extrusion limits the growth and therefore the distribution of this technology.
- The lack of standardization and quality control is found to be a main barrier to use locally recycled materials which is also linked to product liability issues.
- The lack of skills and knowledge about 3D printing in general and on a local scale specifically is seen an important challenge.
- The economics of scale currently involved in the (plastics) recycling industry limits the use of local materials. At the same time, margins on recycled plastics are low due to the low prices of virgin plastics, which is an extra incentive for large scale recycling to reduce recycling costs. Further, the consumers of recycled plastics (e.g. plastic packaging manufacturers) operate at a large scale as well, which stimulates large scale recycling too.
- The lack of efficient and cost-effective small scale recycling equipment.
- When 3D printers become more affordable, value creation increases, but it can become more difficult to capture this value, since competitors can easily adapt their business strategies to the changing market conditions. Therefore it is likely that the competition among businesses will increase.

9.3 Outlook

AM technology offers ways to distribute manufacturing, but it is questionable if this will impact the current centralised material supply. Further research in the area of the economics of scale involved in the material supply and how this influences the opportunities for a more local distribution of materials is recommended. It could also try to quantify the benefits of a more distributed material supply in order to set a target for the efficiency and cost of small scale recycling equipment.

Although most of the challenges are valid for the whole range of AM technologies, the choice to focus mainly on material extrusion has somewhat limited the scope of the study. Since products produced with this technology will have a low functional quality, this technology will mainly be used to produce products such as gadgets, toys and decorations. Manufacturers of high quality products will select other AM technologies, such as powder bed fusion. Further research could focus more on these high quality materials (e.g. metals), although recycling of these materials is already more common practice due to the higher values of the materials.

9.3.1 Potential research questions

To guide future research in this area, a number of research questions have been proposed which address the main challenges found in this study. The questions are grouped by category and are presented in Table 8.

Table 8: Potential research questions

Category	Question
3DP technology	• Could the 3DP technology be improved in such a way that is reduces the amount of skills required? How to increase the usability? • Which opportunities exist to combine/integrate some of the recycling processes for 3D print materials (e.g. filament) in order to achieve cost reductions in the processes involved?
Regulations	• How to assure/certify the quality of recycled materials and of the 3D printed products? • Which standards and testing procedures should be incorporated related to AM technology, materials and products? • How should product liabilities be regulated? • How could regulations support the increased use/recycling of local (waste) materials? • How to enforce the use of (easily) recyclable materials into products?
Economies of scale	• How do economies of scale influence the cost of the recycling processes? • How do economies of scale relate to the required catchment area for specific materials? • Which criteria determine the production cost of 3D printed product allowing distributed manufacturing?
Information	• Which information should be shared / monitored concerning the materials between the material suppliers (e.g. waste handlers) and AM manufacturers? • How could this information be shared? • In which ways information regarding recycling could be included in the final product / CAD (.STL) file? • How could information about the recyclability of materials be shared so that designers could take this into account during the design process?
Education	• How could 3D printing foster the education around the value of materials and recycling/separation? • Which skills are required for 3D printing functional products and how does this limit the distribution of AM technology?
Recycling technology	• What is the market (availability/cost) for small scale recycling systems? • How efficient are small scale recycling systems compared with large scale systems?

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Appendix A – Workshop

Participants

#	Name	Affiliation
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2	Aidong Yang	University of Oxford
3	Alysia Garmulewicz	Saïd Business School
4	Ding Shin Huang	Oxford 3D printing society
5	Dmitry Isakov	University of Oxford
6	Elias Martinez Hernandez	University of Oxford
7	Gerardo Rodriguez	University of Oxford
8	Grit Hartung	Royal College of Art
9	Hannah Stewart	Royal College of Art
10	Hans Veldhuis	University of Oxford
11	Javed Mawji	Ecotech Ltd.
12	Josef Hazi	Oxford 3D printing
13	Joydeep Chakravarty	Saïd Business School
14	Lewis Newton	University of Nottingham
15	Martin Baumers	University of Nottingham
16	Martin Charter	UCA Farnham
17	Matthias Holweg	Saïd Business School
18	Mélanie Despeisse	University of Cambridge
19	Qinrun Ge	Saïd Business School
20	Rhiannon Hunt	UCA Farnham
21	Ritesh Singhania	Saïd Business School
22	Scott Knowles	ObjectForm Ltd.
23	Simon Ford	University of Cambridge
24	William Hoyle	Techfortrade Ltd.
25	Wojciech Piotrowicz	Saïd Business School
26	Yo-Hao Chen	University of Maryland

Summary presentations

Techfortrade by William Hoyle

William Hoyle from the charity organisation Techfortrade presented some of the experiences with 3D printers and collection of waste in developing countries, such as Tanzania. Filament is produced from local waste, supporting local economic development. Plastic waste pickers receive 20 cents per kg in Dar es Salaam. They started a brand, the so-called Ethical Filament, similar to Fairtrade coffee.

The 3D printers itself are fabricated locally as well. The Bill of Material cost for a 3D printer is roughly 130 dollar. Software is used to calibrate the 3D printer to account for the variances among the 3D printers.

He coined the term ‘digital blacksmith’ for producing custom-made parts with 3D printers in a community, linking to the re-introduction of community-scale operations.

William showed an example of a 3D printed microscope, which costs around 240 dollars to produce.

Besides, he pointed at the taxing of waste. Exporting waste to a foreign country (e.g. China) is exempted from taxation; in contrast, using the waste for recycling is subject to tax.

Ecotech by Javed Mawji

Javed presented his company Ecotech which recycles PET bottles into PET flakes. PET has great properties and becomes more increasingly dominant in the plastic packaging industry. Ecotech recycles about 1 million bottles a day and roughly 4 tonnes per hour. Waste from the recycling process includes labels, glue and other waste materials (e.g. metals, other plastics).

PLA (Polylactic acid) has similar properties (density) as PET, therefore it is hard to recycle and it contaminates the PET waste stream at the same time. Therefore, although PLA seems to be environmentally friendly, due to its biodegradability, mixing PLA with other plastics may cause an overall negative effect. In Scandinavia, recyclers have to approve materials used for plastic packaging (e.g. bottles) before they may be sold.

The margins in the plastic recycling market are low. It is a commodity market and the strong GBP results in more imports. Moreover, many companies are talking “green”, but recycled material has to be cheaper. Due to this market situation, recyclers are forced to increase their efficiency and reduce their cost, leading to fewer but larger centralised recycling facilities due to economies of scale. These larger facilities have a larger waste catchment area.

Recycling-minded material selection and product design, may make the recycling process simpler, this could lead to the use of less machineries, hence changing the economical scale of operation.

ObjectForm by Scott Knowles

Scott Knowles from ObjectForm (Fila-cycle) presented some filaments produced by various waste streams. PET flakes from bottles are used to make PET filament, ABS pellets from automotive waste is used to produce ABS filament, PLA filament is made from plastic flakes from yoghurt pots and HIPS filament from HIPS pellets from electrical household appliances, such as fridges.

Availability of large extruders (volume wise) is limited in the UK, because most plastic production machinery is located in China.

The issues around multiple lives of plastics are not well understood yet.

Regulation issues, around what material one can use (e.g. REACH), and what purpose the product can be used for (relating to not only the material, but also the manufacturing process, e.g. the yogurt port case).

Key barriers identified

After the surveys were collected, the main barriers were quickly identified for further discussion. Based on this initial analysis, the following key barriers were found:

1. E: Lack of economies of scale
2. T: Standards and quality assurance (material and products)
3. O/S: Lack of structure for knowledge and information sharing, creating skills, open source
4. E: Low margins achieved in materials recycling
5. R: Regulation regarding safe use of machines and materials
6. S: Education to encourage and increase acceptance of recycling and recycled products

Summary "how to overcome" session

The key barriers were used to discuss opportunities to overcome these. Three groups were formed, after the group discussions their main findings were presented.

Group 1

Related to barrier 3: Who has the authority for open-source info/knowledge sharing? Should this be a centralised organisation? There could be a first mover advantage, similar to other open-source standards (Arduino, RepRap).

Open-source knowledge sharing can be divided into three categories to allow to talk about the kind of information to be shared: (1) processes, (2) hardware and (3) material specs. For processes this seems to be hard and cannot always be shared. For example for recycling, keeping information about the recycling process private gives a company a competitor advantage in market. Hardware is perhaps more useful to be open-source, this lessens the barriers to entry. Information about the specification of materials would support people on local level to understand which materials can be used for specific purposes; this seems to be a big gap to get into the market.

Economies of scale (barrier 1) are constraint by the fact that the supply side (e.g. plastic bottle recyclers, waste collectors/sorters) and the demand side (plastic packaging producers) are both large. There are constraints of the economies of scale, so the different players in the wider eco system should be taken into account.

Leverages of change, what kind of product enables different types of materials from a local level? For example, mass manufacturing of plastics packaging, they probably don't want to differentiate their material streams from local sources, which makes it harder to compete. Complex 3D printed objects, maybe easier to think about such local materials.

Small amounts of materials which may exist in a given locality can become valuable. What is the required scale? Maybe valuable materials (e.g. precious metals) exist, but might currently not be exploited, because the quantities are too small.

Group 2

Related to barrier 6, Fablab movement helps in education which will foster creativity and skills. There seems to be a gap between generations: Younger generations seem to be more enthusiastic about recycling, are more aware of the necessity. This could support the transition to the use of more recycled materials and better sorting of waste materials.

Regarding barrier 3 (info & knowledge sharing). Including more data in the digital .STL file format which is used for 3D printing of a 3D model could support recycling. This could include information about the materials used or materials suitable for the 3D model. A database with materials and products which can be recycled would assist product designers to take the end-of-life stage into account. There seems a lack of understanding how many times the material has been and can be recycled.

Economies of scale seem to be required for material supply for 3D printing, in contrast to manufacturing of products with 3D printers itself.

Digital design sharing: How to protect copyrights or capture value as a designer? This is related to platforms such as Thingiverse.

Group 3

Related to social cost/private cost. It may be an interesting setup, if organisations that receive the feedstock for recycling receive money for recycling (positive thing to remove materials from the waste stream). Align the incentives, remove waste – get money.

Encourage and promote technology adoption, distributed learning centres (Fablabs e.g.). Perhaps understanding better how other supporting technologies fit in distributing technologies.

Hybrid manufacturing technologies, laser cutters, help integrate with 3DP production. Design tools, underlying technology adoption. Thingiverse to download, but ideally design own products. 3D printed eco-system.

Supply side / demand side

Economies of scale: Are the minimum efficient scales on various levels of the system. In recycling area, maybe you need centralised system/catchment area. Use could be local. There may be a mismatch among the actual levels of centralisation.

Materials question. How many times is the material recycled already? What happens? For plastics, the intrinsic viscosity lowers, but this can improved via solid state polymerisation. How do the producers of recycled filament control the quality/standard of the filament, roundness, consistency, material properties? Requirement for little device to ensures filament is up to standards. Certification/standardisation.

There are some clear boundaries, this workshop focused mainly on the small niche related to plastic filament and makerspaces, however 3D printers cover a wider area.

Appendix B – Survey

The survey used to ask stakeholders about what they think are the main barriers for using local materials as supply for 3D printing, can be found on the following two pages.

Name: Affiliation: Email:

What barriers exist for using local materials as supply for 3D printing?

	Which **technical** barriers exist?	
T1		Low – **Severity** – High 1 2 3 4 5 **Likelihood to overcome** 1 yr 5 yr 10 yr 30 yr never
T2		Low – **Severity** – High 1 2 3 4 5 **Likelihood to overcome** 1 yr 5 yr 10 yr 30 yr never
T3		Low – **Severity** – High 1 2 3 4 5 **Likelihood to overcome** 1 yr 5 yr 10 yr 30 yr never

	Which **economic** barriers exist? (<u>*please note*</u>*: there is also a section about organisational barriers*)	
E1		Low – **Severity** – High 1 2 3 4 5 **Likelihood to overcome** 1 yr 5 yr 10 yr 30 yr never
E2		Low – **Severity** – High 1 2 3 4 5 **Likelihood to overcome** 1 yr 5 yr 10 yr 30 yr never
E3		Low – **Severity** – High 1 2 3 4 5 **Likelihood to overcome** 1 yr 5 yr 10 yr 30 yr never

	Which **social/cultural/behavioural** barriers exist?	
S1		Low – **Severity** – High 1 2 3 4 5 **Likelihood to overcome** 1 yr 5 yr 10 yr 30 yr never
S2		Low – **Severity** – High 1 2 3 4 5 **Likelihood to overcome** 1 yr 5 yr 10 yr 30 yr never
S3		Low – **Severity** – High 1 2 3 4 5 **Likelihood to overcome** 1 yr 5 yr 10 yr 30 yr never

	Which **organisational** barriers exist?	
O1		Low – **Severity** – High ① ② ③ ④ ⑤ **Likelihood to overcome** 1 yr 5 yr 10 yr 30 yr never ○ ○ ○ ○ ○
O2		Low – **Severity** – High ① ② ③ ④ ⑤ **Likelihood to overcome** 1 yr 5 yr 10 yr 30 yr never ○ ○ ○ ○ ○
O3		Low – **Severity** – High ① ② ③ ④ ⑤ **Likelihood to overcome** 1 yr 5 yr 10 yr 30 yr never ○ ○ ○ ○ ○

	Which **regulatory** barriers exist?	
R1		Low – **Severity** – High ① ② ③ ④ ⑤ **Likelihood to overcome** 1 yr 5 yr 10 yr 30 yr never ○ ○ ○ ○ ○
R2		Low – **Severity** – High ① ② ③ ④ ⑤ **Likelihood to overcome** 1 yr 5 yr 10 yr 30 yr never ○ ○ ○ ○ ○
R3		Low – **Severity** – High ① ② ③ ④ ⑤ **Likelihood to overcome** 1 yr 5 yr 10 yr 30 yr never ○ ○ ○ ○ ○

Based on all the barriers, what is in your opinion the top 3 of most important barriers?

1. (*e.g. E2*)	**2. (*e.g. T1*)**	**3. (*e.g. O1*)**

Thank you for your time! Please treat yourself to a nice lunch! :-)

3DP-RDM
3D printing-enabled re-distributed manufacturing

DEPARTMENT OF ENGINEERING SCIENCE

SAID BUSINESS SCHOOL

UNIVERSITY OF OXFORD

Appendix C – Raw survey data

#	Affiliation category	Category	Barrier	Severity (1-5; 0=NA)	Likelihood to overcome (years,0=NA)	Top barriers
1	Design	Technological	Outputs: What can be currently printed (1: small scale prototyping, vs. 2: large scale)	0	7	
1	Design	Technological	Local material that regenerates (Biomimicry principles)	4	20	3
1	Design	Economic	Incentive system for short & long term profits & low cost vs. high cost value creation (economic, environmental, cultural)	2	3	
1	Design	Economic	Product service systems	0	0	
1	Design	Social	Recycle, reuse, repair ***, as well as urban mining and 'custodian'/prosumer	2	3	
1	Design	Organisational	Intransparencies and disconnected value chains across stakeholders	0	3	
1	Design	Organisational	Open data & hardware for knowledge and skill sharing	4	3	2
1	Design	Organisational	Circular business models	3	3	1
1	Design	Regulatory	IP, trademarking forward sensible / open knowledge sharing	0	0	
2	Engineering	Technological	Processes/platforms for distributed additive manufacturing are not clear yet with current extrusion-based systems, there are severe problems	4	10	
2	Engineering	Technological	Stability/reliability of distributed recycling systems (only for filaments!) is not sufficient yet	3	5	
2	Engineering	Technological	Health risks of operator exposure to distributed polymer recycling processes are of concern	2	5	
2	Engineering	Economic	Scale economics in polymer recycling for AM feedstocks are poorly understood	3	10	
2	Engineering	Economic	Use phase - utility of products created via distributed additive processes (filament deposition) is questionable)	5	30	
2	Engineering	Social	General population may not be interested in involvement in distributed manufacturing/recycling configuration --> gravitate towards centralisation	3	30	
2	Engineering	Organisational	Unavailability of expertise on the distributed level	3	10	
2	Engineering	Organisational	Critical mass / catchment area may not be sufficient (if thinly populated)	3	10	
3	Engineering	Technological	Local skills and awareness about 3D printing capabilities and limitations	4	10	1
3	Engineering	Technological	Availability of the local materials	3	30	3
3	Engineering	Technological	Lack of appropriate historical data for 3D printed product	5	30	
3	Engineering	Economic	High cost of setting up 3D printing facilities	5	30	
3	Engineering	Economic	Unit cost of materials and recycling cost	4	10	
3	Engineering	Social	Experience in other manufacturing methods	3	10	
3	Engineering	Social	Resistance to change	3	10	
3	Engineering	Organisational	Lower level of skill in the 3D printing industry	5	30	

3	Engineering	Organisational	Willingness of management in industry to accept 3D printed products	4	10	
3	Engineering	Regulatory	Local legislation	5	30	2
3	Engineering	Regulatory	Lack of standards for 3D printed parts	4	10	
4	Engineering	Technological	Local skills and expertise	4	0	
4	Engineering	Technological	Cheap recycling methods to compete with virgin producers	4	10	
4	Engineering	Technological	Usage for engineering level applications	3	10	
4	Engineering	Economic	Access to build up significant recycling/reproduction centres	3	10	
4	Engineering	Economic	Virgin materials competiveness with non-virgin sources	3	0	
4	Engineering	Social	Knowledge of recyclability	5	10	
4	Engineering	Social	Trust in supply, where are these plastics from?	2	5	
4	Engineering	Organisational	Poor sorting of waste materials by local councils	3	5	
4	Engineering	Regulatory	Legislation issues for recycling and reuse	4	10	
5	Engineering	Technological	Integration of functional components (e.g. electronics) on 3D-printed products for end-users	0	0	
5	Engineering	Economic	Need to go beyond economic argument to make local materials competitive with other sources which benefit from economies of scale, e.g. contribution to regional development	0	0	
5	Engineering	Social	Educating engineers & designers	0	0	
5	Engineering	Social	Improve quality of recycled plastics by engaging with general public (e.g. collection of "clean waste" requires consumers' cooperation)	0	0	
5	Engineering	Organisational	Adapting the business model to a more local/distributed supply chain (for existing companies)	0	0	
5	Engineering	Organisational	Developing industrial symbioses (waste=food): Issues of strategic alignment & trust to establish collaborations	0	0	
5	Engineering	Regulatory	Certification of (recycled) materials when processed locally	0	0	
6	Engineering	Technological	Absence of small-scale, economically efficient recycling systems (i.e. machines that create the material input for 3DP - plastics, metals, ceramics & others)	0	0	1
6	Engineering	Technological	Recycling systems for non-filament materials	0	0	
6	Engineering	Technological	Local bio-polymer production systems don't exist that could produce	0	0	
6	Engineering	Economic	Availability of the local materials and their sourcing + processing	0	0	
6	Engineering	Economic	Markets for recycled materials - materials produced by large scale operations increase supply, lowering prices of materials, reducing incomes for small scale operators	0	0	
6	Engineering	Social	Understanding of 3DP in business & perceived scales & scopes of application	0	0	
6	Engineering	Social	Understanding (or lack) of circular economy & how systems need to be implemented	0	0	
6	Engineering	Social	Perceptions of virgin vs recycled materials	0	0	
6	Engineering	Organisational	The desire of 3DP firms (e.g. 3D Systems, Stratysys) to have proprietary materials on which they can earn revenues	0	0	2
6	Engineering	Organisational	Need for partnerships and collaborations	0	0	

6	Engineering	Regulatory	Product liability from materials quality	0	0	3
7	Business	Technological	Will 3D printing ever get to a point where it becomes a competitor to current highly advanced plastic technology?	4	never	
7	Business	Economic	Why would corps ever choose to use 3D printing? It seems much more expensive?	5	30	
7	Business	Economic	3D printing doesn't seem time efficient compared to current production rate	4	30	
7	Business	Economic	Current 3D printed items (and recycling in general) do not provide a better quality	4	30	
7	Business	Social	The 3D printing market doesn't appear to be very profitable. Even if people want to invest, they might wait till the technology is more advanced	4	10	
7	Business	Organisational	Since plenty of products are produced overseas, what action can we take to affect interests in using 3D technology?	3	10	
7	Business	Regulatory	Just wondering, to what extent is the UK government supporting financial wise to this area?	0	0	
8	Design	Technological	Availability of equipment e.g. extruder example (needs to be improved)	4	5	
8	Design	Technological	Includes - material e.g. material innovation, etc.	4	5	1
8	Design	Technological	Testing/quality of materials e.g. consistency	4	5	
8	Design	Economic	Cost of recycled material vs virgin materials (given oil prices)	4	0	
8	Design	Economic	Cost of equipment/etc	4	5	
8	Design	Economic	Products that can be made that have higher value	4	5	
8	Design	Social	Familiarity - needs finding --> tech transfer	4	5	
8	Design	Social	Lessons learnt from use (how collected)	3	10	
8	Design	Social	Limit to expansion of maker/modifier/fixee movement	3	5	
8	Design	Social	How experimentation moves into products (scale up)	3	5	2
8	Design	Organisational	Development of open groups to share knowledge in & outside companies e.g. hackspaces	4	5	3
8	Design	Regulatory	Quality of materials (standards)	4	7	
8	Design	Regulatory	Quality of printing from machines & peripherals e.g. extruders/sources, etc. (standards)	4	5	
9	Business	Technological	Impurities: Are there more cost efficient ways of removing impurities?	3	10	
9	Business	Economic	There needs to be sufficient scale	2	10	
9	Business	Social	People understanding the potential uses of 3D printing --> will enable scale and tip regulations	2	10	
9	Business	Regulatory	One barrier is definitely the lack of testing & standards that go into making sure 3D products can be used (e.g. yoghurt containers)	2	7	
10	Business	Technological	Quality of the finished product	4	5	2
10	Business	Economic	Economies of scale. How large is the requirement for local materials for someone to manufacture filaments?	3	5	
10	Business	Economic	Who will buy 3D printed local materials? The sales volume?	3	5	3
10	Business	Economic	The cost of 3D printed products vs traditional manufacturing	3	7	1
10	Business	Social	Behavioural barrier in terms of segregating feedstock (severity depends on the country)	3	10	

10	Business	Regulatory	For food packaging - contamination	4	never	
10	Business	Regulatory	Strength of materials for some used cases	3	5	
11	Business	Technological	Recycling metal waste	2	10	
11	Business	Technological	Acceptability of recycled plastic for food storage	3	10	
11	Business	Economic	Currently the recycled materials need to be cheaper than virgin materials	5	never	1
11	Business	Social	Acceptance or realising the need of using recycled plastic over virgin plastic	5	5	3
11	Business	Social	Government laws forcing use of recycled plastic	0	5	
11	Business	Social	Trust on recycled plastic for use in critical environments - food, gears	3	30	
11	Business	Regulatory	Government regulation forcing the use of recycled plastic	3	5	2
12	Design	Technological	Patents on new/improved 3D-printing methods preventing innovative, small start-ups from marketing cheaper & more accessible versions for local communities/individuals, e.g. FormLabs lawsuit	4	30	
12	Design	Technological	Improving 'green axis' strength in FDM prints (Other technologies may provide higher quality prints, but are less accessible, more expensive, more implications for health & safety & don't facilitate economic recycling of plastic waste)	3	5	
12	Design	Technological	Widening the selection of possible 3D-printed materials as well as multi-material printing (to produce components that consist of plastic, ceramic & metal parts). This would widen the market for recycling of different materials & the market for 3D printed goods	3	5	
12	Design	Economic	Start-up costs for equipment, especially as the 3D-print industry is in its early stages & is constantly being improved (i.e. investment in today's tech could be rendered obsolete, fairly quickly)	4	5	1
12	Design	Economic	Cheap virgin/raw materials making market for recycled materials poor/stagnant	4	1	
12	Design	Economic	Awareness & demand for customised 3D-printed products is still relatively low, but is growing. Increased demand will help to justify investment in start-ups & equipment	4	1	
12	Design	Social	Poor recycling rates amongst consumers. Need greater awareness & incentives. Could 3D printing provide the motivation for consumers to recycle more of the household waste?	5	never	2
12	Design	Social	Governmental policies to promote recycled materials over virgin	4	1	
12	Design	Social	Open sourcing of more designs, software & hardware plans/instructions needed to reach developing communities	3	1	
12	Design	Organisational	Reduced R&D investment as part of recession	3	5	
12	Design	Organisational	Those in extractive / oil industry are very wealthy & have power/influence on regulators & will want to retain market share over recyclables	5	never	
12	Design	Organisational	Time & money to explore the potential of new technologies - ' business as usual' / 'industrial inertia'	4	5	
12	Design	Regulatory	Subsidies for recycled materials & added taxes to non-renewables needed	5	never	
12	Design	Regulatory	Health & safety regulations & the need to invest in thorough testing	4	1	3
12	Design	Regulatory	More generally with 3D printing - safety & the printing of restricted products e.g. guns could damage the reputation of the tech as a whole, incurring additional regulations & restrictions on the technology	3	5	
13	Business	Technological	Too many types of plastic (despite similar use)	5	10	
13	Business	Economic	*** (global demand)	0	0	
13	Business	Economic	Low customer involvement (not all customers are "green") - customers won't pay more for product	3	30	

13	Business	Social	Low end-customer pressure on manufacturers to use recycled materials	0	0	
13	Business	Organisational	Different collecting models for product *** (not always efficient)	3	30	
13	Business	Organisational	Not well established metrics to monitor return/recycle supply chain	2	30	
13	Business	Regulatory	Lack of EU-side regulations	5	10	
13	Business	Regulatory	Lack of regulations to use % of recycled materials	0	0	
14	Business	Technological	Cost of recycling sorting equipment	3	5	1
14	Business	Economic	Economies of scale in mass manufacturing	5	10	
14	Business	Economic	Price of primary plastics	2	30	
14	Business	Organisational	Information barriers in sourcing	4	5	2
14	Business	Organisational	Coordinating small-scale sources of waste	3	5	3
14	Business	Regulatory	Specifying the treatment of waste by certain large-scale technology	2	10	
15	Engineering	Technological	No tracking system for the origin of plastics, lack of information about previous use of plastics	0	0	
15	Engineering	Economic	The cost of the 3D printing process itself. It does not make products cost-effective yet	0	0	1
15	Engineering	Social	Lack of knowledge about 3D printing capabilities	0	0	
15	Engineering	Social	Low quality 3D parts compared to injection molding. (finished, mechanical properties)	0	0	2
15	Engineering	Organisational	Information is widespread not shared	0	0	
15	Engineering	Regulatory	Not clear what the regulations are for 3D printed components for commercial applications	0	0	
16	Engineering	Technological	Achieve proper quality & purity	5	5	1
16	Engineering	Technological	Use minimum pre-processing to extend life i.e. using raw material direct into 3DP instead of converting to filament first	5	5	2
16	Engineering	Technological	Capability to use composites or create new composite blends out of the waste plastic and possible create new materials	3	3	
16	Engineering	Economic	What products to make	5	5	
16	Engineering	Economic	pricing of raw material and economy of scale	5	5	
16	Engineering	Social	Education to improve separation at household level in order to keep quality	5	10	3
16	Engineering	Social	Education and acceptance of products by consumers	5	10	
16	Engineering	Organisational	Organise collectors	5	10	
17	Engineering	Technological	Sorting materials	4	10	
17	Engineering	Technological	efficiency of small scale machinery	3	5	1
17	Engineering	Economic	price of virgin plastics/materials	4	10	3
17	Engineering	Economic	capital cost of small scale machinery	4	5	
17	Engineering	Economic	cost of transportation related to scale	3	0	
17	Engineering	Social	Awareness of value of materials to achieve better waste sorting	4	30	

17	Engineering	Organisational	Use materials which are recyclable	3	5	
17	Engineering	Regulatory	Cost of waste is still low, could be regulated more	3	5	2
17	Engineering	Regulatory	Safety regulations regarding materials and 3D printed products	2	10	
17	Engineering	Regulatory	CO2 pricing (if local manufacturing is more energy efficient, this will stimulate it)	2	20	
18	Engineering	Technological	Quality-assured material supply	4	5	1
18	Engineering	Technological	small-scale material processing facilities	3	10	
18	Engineering	Economic	Fluctuations of material price	3	10	
18	Engineering	Organisational	Coordination across the business chain to reduce risk & increase stability	3	10	2
18	Engineering	Regulatory	Regulation with the use of materials (e.g. REACH)	3	3	3
18	Engineering	Regulatory	Regulation pertaining? To processing/products facilities?	3	10	
19	Industry	Technological	Scalability of recycling process (equipment, etc.)	4	5	1
19	Industry	Technological	Range of materials available as usable filament	3	5	
19	Industry	Technological	range of printing methods currently feasible	3	5	
19	Industry	Economic	Scale economics of recycling	5	5	2
19	Industry	Social	Lack of awareness of value of recycling	5	5	
19	Industry	Social	Lack of reward system for local recycling	3	3	
19	Industry	Organisational	No players currently exist in the value chain to organise local materials recycling for 3DP	4	5	3
19	Industry	Regulatory	Depending on territory - fiscal	4	10	
19	Industry	Regulatory	Safety standards (e.g. REACH)	5	never	
20	Industry	Technological	Sorting technology needs to improve	4	5	
20	Industry	Economic	Low price of oil - cheap virgin materials	5	5	1
20	Industry	Economic	PRN/PERN - stimulating export of feedstock	5	5	2
20	Industry	Economic	Strong pound - favouring imports	5	5	3
20	Industry	Social	Recycling still not wide spread	5	5	
20	Industry	Social	Marketing dominance - e.g. lucozade bottles, instead of environmental impact	3	5	
20	Industry	Organisational	PERN/PRN organised by DEFRA - doesn't cost them anything so they don't reform it	5	5	
20	Industry	Organisational	Governmental funding for recycling being cnt? (to local authorities)	5	5	
20	Industry	Regulatory	PRN (again)	5	5	
20	Industry	Regulatory	REACH not being implemented (unfair imports)	4	5	
21	Industry	Technological	Testing of materials qualities, strengths (tensile), toughness, etc. These tests are not currently being under taken as widely as they should be	4	5	
21	Industry	Technological	Availability of machines capable of creating materials for 3D printing is low	4	5	1

21	Industry	Economic	Local spending habits and local money that could be used ot purchase technical machinery is not always available	4	10	
21	Industry	Social	The ethos behind recycled plastics and the goods created from these plastics must overcome the negative stigma surrounding the terminology "recycled"	4	10	
21	Industry	Social	Larger manufacturers could create recycled plastics from local sources	3	5	
21	Industry	Social	Awareness surrounding the amount of value within a discarded product needs to be increased	5	10	
21	Industry	Organisational	As small business enter the market a more distributed model will need to be adopted as the lives of plastic used in 3D printing is increasing in complexity	4	5	
21	Industry	Organisational	Businesses need to be more distributed	0	0	2
21	Industry	Regulatory	There are very little regulatory barriers behind the printers themselves. We will see an increase in machine regulation	4	5	
21	Industry	Regulatory	Plastic regulation exists within the industry already, yet new businesses are unaware of this. Education is required	4	5	
21	Industry	Regulatory	Machine and plastic regulation	0	0	3
22	?	Technological	Proprietary technologies and closed-sourced technologies owned by existing material supplier make it very hard for other players to participate as well as innovation needed	5	0	
22	?	Economic	Economy of scale required to recycle and/or produce local materials	4	0	2
22	?	Economic	Propriety technologies make the manufacturing/recycling process unnecessarily expensive	0	0	
22	?	Organisational	It's difficult to organise local materials supply at scale	4	0	
22	?	Organisational	Close-sourced ecosystem	0	0	1
23	?	Technological	Lack of machine manufacture in the UK has availability of large scale processing machines	0	0	
23	?	Social	Need & understanding of tech & materials	0	0	
23	?	Social	Aesthetic sense around desirability of optimum processes environmentally	0	0	
23	?	Organisational	Need for new forms of organisations not built on old logistics	5	30	
23	?	Organisational	Understanding of distributed infrastructure & locally aware industry ecosystems in terms of risk, value & responsibility	4	10	
23	?	Organisational	Not sure this fits here: Likelihood of redistributing existing demands, processes & material choice/use, not stimulating a 'better' design of local material 3D printing eco-systems	0	0	
24	?	Technological	3D printing product quality, cost	4	0	
24	?	Technological	mass production using 3DP	4	0	1
24	?	Technological	Quality of products and powder	0	0	2
24	?	Economic	Cost of recycling vs. cost of production	4	never	
24	?	Economic	3D printing efficiency for mass production far from 100% success rate	4	10	
24	?	Economic	cost of 3D printers	2	3	
24	?	Organisational	If it was efficient wouldn't there already be vertically structured companies? Material supply --> production	3	0	
24	?	Organisational	High barrier to penetrate metal powder production (gas atomisation) + achieve the required quality	0	0	

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