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A Regional Integration Study for Plastic Recycling Supply Chains

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Abstract
Plastics have facilitated the human life and development of civilisation in many aspects thanks to their positive attributes. However, it has also been at the centre of discussions about its negative impacts, especially on the environment. This controversy has increased the importance of recycling capabilities both globally and locally, while it also suffers from a variety of challenges. This study, therefore, has investigated the opportunities to integrate the plastics recycling supply network of the North East of England and demonstrated the regional relationships, capabilities, existing challenges and potential opportunities for the development of the sector and the region.

Keywords: Plastics recycling supply chains, Supply chain integration, Supply chain customisation

Introduction

Plastics are important materials for our daily lives as they are utilised for various perspectives in all sectors and purposes. In line with this utility, the amount of plastics produced has gradually grown since the beginning of plastics production in the 1950s and reached 367 million tonnes of production in 2020. Over these years, another aspect related to plastics has also developed: the management of plastic waste. Due to the nature of the plastic material, it is not easily disposed of in nature itself. Even though it might not be considered at the beginning of the plastics era, the waste of used and disposed plastics has accumulated since then. Not long after, this waste problem and its negative effects on the world were noticed and actions were taken towards solving it, of which one of the leading practices is recycling. Even though the efficiency of recycling has been improving over time, overall only 5-10% of the accumulated waste plastics are considered to be recycled so far, while the remaining majority has either been incinerated or sent to landfill. However, exemplary recycling rates -such as of EU28 + Norway and Switzerland- of 31% can show the increased efforts and our current capability to deal with the plastics waste problem at the moment.

It is essential to highlight that this improvement has not been realised in one day. In opposite, it has taken numerous tiny steps from various aspects like machinery improvement, invention of novel recycling methods and better material separation techniques. They all have made the situation a bit better and got us closer to the complete solution of the plastics waste and maximum recycling performance. However, industrial recycling capability is still under development and requires improvements in these aspects as well as various others.

One of these aspects is the supply chain efficiency of the plastics recycling sector. Starting with the manufacturing industry, supply chain management has improved the efficiency of firms by taking the level of competition from the business level to the effective management of the whole supply chain. Then the concept and its application have been adopted by many other sectors such as food, apparel or construction. However, in the plastics recycling sector, many studies show that comprehension and application of the supply chain concept are not as advanced as in the other sectors. While this deficiency of comprehension brings many difficulties for the sector, it also results in missing opportunities. Therefore, the plastics recycling sector requires further research and improvements with a lens of supply chain management and integration to better identify the gaps and challenges in the sector as well as further opportunities and best practice applications.

Moving from this research requirement, this study aims to unearth the opportunities of supply chain integration in the plastics recycling sector and uses the North East region of England as the case territory. The region is enriched with an intense investment in processing and petrochemical industries. Therefore, it is believed that it is a suitable area to conduct the project and to produce promising development results that will bring improvements for the region and will also be an exemplary practice for the rest of the UK and other industrial sectors.

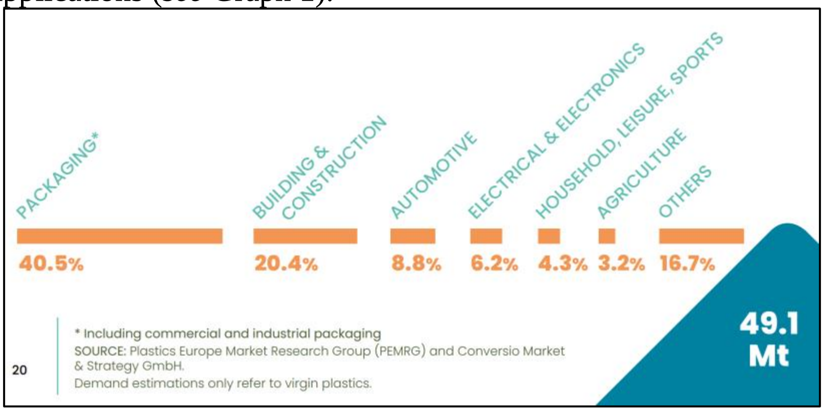
To achieve the main targets of identifying the supply chain-related sector challenges and producing roadmap strategies for their solutions and further opportunities, this study pursued the answers to the following research questions:

- What are the actors of a plastics recycling supply chain?
- What are the required capabilities of those actors in the sector?
- How do the challenges and opportunities vary according to the roles of the actors in the sector?
- How can supply chain customisation enhance the integration capabilities of the actors in plastics recycling supply chains?

Literature Review

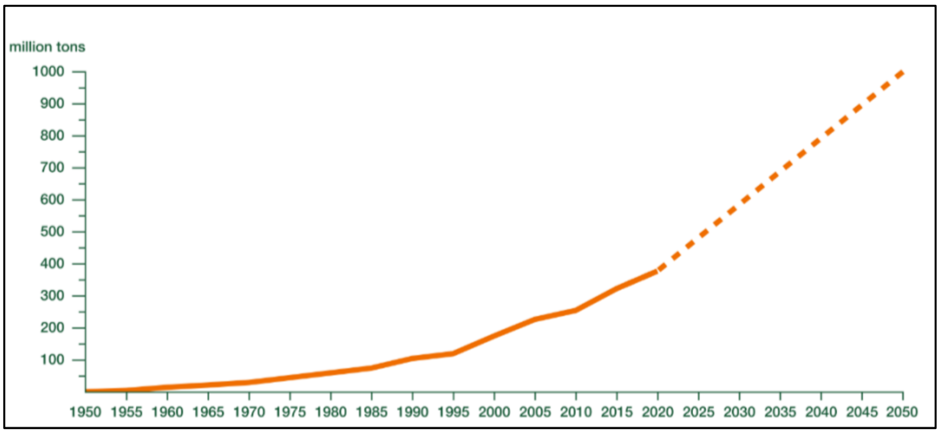
Plastics Production and Supply Chain

Since its first commercial-scale production in the 1950s, plastics have been utilised for a wide range of purposes from industrial applications to everyday items. While packaging has been the major application area, plastics have been crucial for other industries such as construction and electrical applications (*see* Graph 1).



Graph 1 EU27+3 converters plastics demand by segments 2020 (Plastics Europe, 2021)

In line with the increasing utilisation areas, the production of plastics has also gradually increased and in 2020, 367 million tonnes of plastics have been produced (*see* Graph 2), making the total produced plastics amount approximately 8.3 billion tonnes so far. While the annual plastics production amount is expected to double by 2034 and reach about 1,2 tonnes of annual production by 2050 (Lamberti et al., 2020).



Graph 2 Global plastics production amounts in last 5 years (Tenhunen and Pöhler, 2020)

Besides its widespread applications, another antecedent of increasing plastics popularity and production was related to the low cost of the main raw material, petrochemicals. Although various plant-based raw materials like cellulose from cotton, furfural from oat hulls, oil from seeds and various starch derivatives were also utilised for plastics production at the beginning of plastics history, later petrochemicals have been the mainstream plastic raw material. It is estimated that 6% of the oil produced in the world is used as feedstock for plastics polymer synthesis (Lamberti et al., 2020).

Production of plastic materials, hence the forward plastics supply chain consists of three main stages. The first stage is the processing of preplastics and starts with the extraction of crude oil. Extracted crude oil is then transported to the petrochemical refinery plants where it will be processed into various petrochemical outlets (Wong, 2010). The second stage occurs in these refinery plants and covers the activities that will create the primary plastics from the crude oil. Among the crude oil outlets, Ethane and Propane derivatives are utilised for the production of Ethylene and Propylene under high-temperature furnaces. Next, by combining with various catalysts in a reactor, these materials are turned into powdered-formed plastics polymers, named ‘fluffs’. Lastly, fluffs are blended with required additives and melted in extruders to produce plastics ‘pellets’. Pellets can be accepted as the primary form of plastics and shipped to the plastics material producers (Wong, 2010). In the last stage, pellets are transformed into their final consumption forms such as packaging, kitchen utensils, water pipe, window frames or electronic equipment parts. Manufacturers can use various required additives and technical activities like extrusion and injection moulding to reach the final desired form of plastics material (Wong, 2010). Mentioning the extrusion and moulding activities, it is also critical to mention and include the manufacturer of plastics production machinery in the plastics supply chains.

Plastics, Sustainability and Recycling

To better understand the facts behind plastics preference and popularity to be utilised in various application areas and therefore being demanded and produced in an increasing trend, initially, it would be essential to understand the characteristics of plastics products.

Firstly, being a petroleum-based material, it has a low production cost (Lamberti et al., 2020). Secondly, its mechanical and barrier properties such as being light, inert, flexible and durable make it superior to its alternatives in occasions of demanded product specifications, ease of storage and transport and requirement for maintenance (Khaertdinova et al., 2020). Next, it is a clean and hygienic material and that makes it a preferable option for producing all sorts of containers that require complete isolation from contamination such as food packaging or medical equipment and consumables. Lastly, its versatility also brings a critical superiority to plastics. Depending on their chemical components and the manufacturing additives, plastics may provide a wide range of versatility for the customers, i.e., from single-use easily tearable films to long life and firm water pipes (Wong, 2010).

These characteristics have also a direct impact on the sustainability profile of plastics, starting with three primary environmental aspects: critical resource utilisation, energy utilisation and emission output. The following table presents the superiority of the plastic bag over its paper alternative when its reusability and recyclability characteristics are taken into consideration:

	Polyethylene 1,500 pcs (smaller capacity), 6 kg	**Paper** 1,000 pcs, 52 kg	**Reusable nonwoven polypropylene** 1,000 pcs, 42 kg		**Reusable polypropylene with 40 % recycled content** 1,000 pcs, 42 kg	
	1 use	**1 use**	**1 use**	**8 uses**	**1 use**	**8 uses**
Non-renewable energy (GJ)	763	2,620	3,736	467	2,945	368
GHG (t/CO_2eq)	0.040	0.080	0.262	0.033	0.182	0.023
Fresh water consumption (L)	220	3,785	1,613	322	946	151

Table 1 Comparison of plastics with other materials (Klemeš et al., 2020)

Beyond these primary impacts, the utilisation of plastics in various applications brings further environmental benefits. Some examples are easier transportation and less transportation emission due to the material's lightweight, reduction in energy consumption in building heating due to its insulation power, higher efficiency and energy savings when used in technology applications like LCD screens, and contributing to reduction of waste by extending the lifetime of packaged products. In line with these energy and resource savings, plastics utilisation also brings economic benefits in the form of cost reduction in production, transportation, sale and maintenance.

Lastly, plastics have also some positive impacts on the social aspect of sustainability. Initially, easing the production of various materials, plastics contributed to the evolution of technology that we are facilitating at the moment. Examples can range from everyday technology equipment to the developments in travel by enabling reduced mass for cars, ships, trains, aircraft and even space exploration vehicles. Besides, its impacts on food and water safety have increased the quality of life. Plastics has also an unreplaceable place in the health care industry in the form of single-use medical equipment and it is even getting more important with the advancements in artificial organ and transplant research (Parashar and Hait, 2021). In line with all these improvements in human life, these evolutive impacts seem to continue in the future considering the recent developments such as active, smart or biodegradable packaging solutions (Dey et al., 2020).

On the other side of the coin, there are negative consequences of plastic consumption as well. The most prominent concerns with the use of plastics are those related to environmental considerations, which have gained public interest in recent years following an increasing number of studies from various stakeholders of society including academia, international organisations and media (Dey et al., 2020). The major problem of plastics arises when they reach their end of life and become waste. In line with its popularity and increasing applicability, nearly 8.3 billion tonnes of plastics produced so far since the 1950s where a proportion of 30-50% has been predicted to be sent to landfill and another third to be incinerated. The significance of this plastic waste accumulation problem can also be seen in the oceans. Every day, up to 8 million pieces reach the ocean, making it between 4.8 and 12.7 million tonnes per annum (EU Parliement, 2020), of which 80% comes from the land via inland waterways, wastewater outflows (Dey et al., 2020; Klemeš et al., 2020). Considering the increasing trend of plastic production, it can be clearer to see the criticality of environmental concerns.

The negative effects of plastics can relate to their adventageous characteristics in some aspects. The first set of problems stems from the petroleum-based nature of plastics. Since petroleum is a non-renewable type of resource and composes nearly 98% of total plastic production, plastics initially cause the depletion of limited natural resources (Zhao, Cornish, and Vodovotz, 2020). Besides, this characteristic harms plastics' degradation in nature. When plastics slowly degrade, they break down into pieces with smaller sizes and lower densities by the impacts of weather (rain and wind) and ultraviolet sun rays. According to their sizes, these particles are called micro or nano plastics. The most prominent harm of micro and nano plastics to the environment occurs with their inhibition of the growth of algae in the oceans, which are vital sources of oxygen(Sjollema et al., 2016).

The affordability of plastics also creates undesired consequences. Being a petroleum-based and mass-produced material, plastics are manufactured and sold at low prices (Klemeš et al., 2020). This advantage expectedly results in the increase of single-use applications by making them about 40% of the total plastic waste and also makes the materials easily disposable. Single-use plastics (SUP) have a shorter lifetime (varying between a few hours and months), and lose nearly all of their economic value (more than 95%) after their single use (Dey et al., 2020).

Besides the environmental impact, plastics also cause social problems, due to their potential threats to human health. This mainly occurs through the infiltration of plastic particles into the food chain via the consumption of fish and other sea creatures (Segran, 2021). Experimental studies by Sanchez et al. (2014), Fu and Wang (2019) and Barboza et al. (2020) respectively demonstrate microplastic contamination in various sea creatures in the freshwater rivers of France, China and the North-East Atlantic Ocean. Secondly, plastics also harm the food chain by providing the migration of toxic contaminants such as heavy metal elements, organic additives and reaction or breakdown products when they are used for single-use purposes. Lastly, microplastics can impact human health via airborne contamination. By clinging to fruits and vegetables, they infiltrate the food chain. Airborne plastics can also be inhaled directly by humans, especially by industrial workers in the production of plastic materials (Dey et al., 2020). By all these means, microplastics bioaccumulate in the human body. Earlier studies show that human plastic consumption can range from 74,000 to 121,000 particles per year, and those accumulated plastics in the human lungs can stay for 180 days without any size reduction. Although ingestion of microplastics is not considered life-threatening, they cause physiological problems ranging from oxidative stress to carcinogenic behaviour (Lamberti et al., 2020).

Lastly, the transition of plastics into waste also results in some economic implications. Although there is not a comprehensive quantification of plastics' impact on the environment and there is an essential need for further research in Life Cycle Analysis (LCA), it is predicted that plastics going to landfill causes an economic loss of £62–92 billion so far (Lamberti et al., 2020).

Evaluating the environmental considerations regarding plastics, a dual-perspective conclusion can be drawn. On one side, they are highly important materials with various positive aspects and hence utilised in numerous applications. However, on the other side, end-of-use plastics must be managed carefully to avoid their negative impacts. In order to maximise plastics' benefits and minimise harms, various sustainability strategies from different disciplines are proposed, especially from sustainability and circular economy fields such as refraining, redesigning, reducing, reusing, repairing, refurbishing, remanufacturing, repurposing, recycling and recovery and re-mining (Wong 2010; Klemeš et al., 2020). Despite not all of these strategies necessarily applied for the sustainability of plastics, the 'Waste Hierarchy' framework (see Figure 1) can help identify the most related and effective ones.

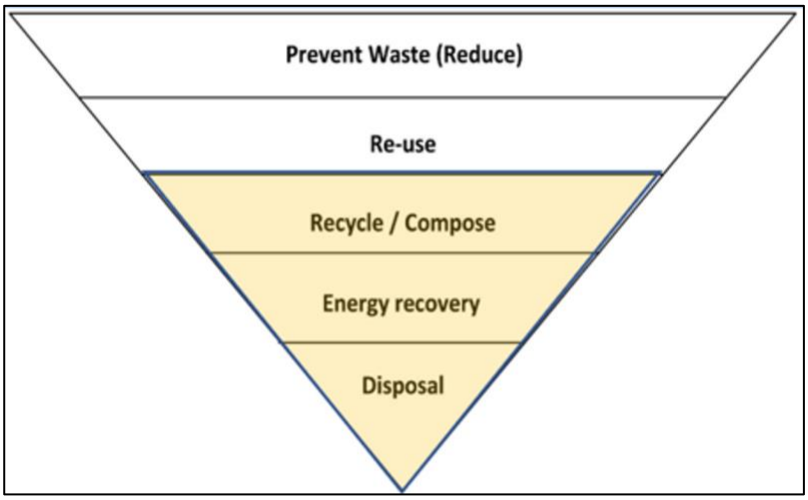


Figure 1 Waste hierarchy pyramid (Wong, 2010)

The first three strategies are mostly realised through the change in the behaviour of consumers, although firms in plastics SCs (e.g., manufacturers and retailers) apply various activities to increase customer awareness of the issue and to change their behaviour. The remaining strategies – recycling and recovery, on the other hand, require plastics recyclers' direct involvement and management. Recycling of plastics holds an important place in sustainability as it can be accepted as a battle against the entropy of plastic waste accumulation over the years. It extracts the plastic waste from the waste stream which should normally end up in landfill and puts it back into the material cycle as a secondary material that will be utilised to produce outputs of similar or lower quality. In other words, it creates a closed-loop and increases the lifetime of the initial raw material. Considering the proportion of recycled material is at around 5-10% and the economic loss of remaining unrecycled waste reaches up to £62-92 billion, the importance of recycling and actions to improve the related capabilities is gradually increasing (Lamberti et al., 2020).

Plastic Recycling Processes

Providing a reverse supply chain, recycling is composed of various steps such as collection, sorting, separation, and process of recycling. In addition, this section will also explain the types of plastics, considering their critical impact on the selection of recycling path.

Waste materials are collected to be recycled in various schemes. Firstly, most of the plastics are collected as mixed with all other wastes that have the potential to be recycled such as glass, paper, cardboard, tin or other metals. Mixed waste generally comes from the municipal as the post-consumer waste, and is also named the kerbside collection. The second scheme is the separate collection scheme. Different types of plastics can be separately collected in purpose.

While the organisations can implement such collection schemes, supermarket retailers also recently started to have separate collection schemes for their customers. Lastly, different types of plastics can be directly collected from the organsations in a single stream, especially the commercial and industrial plastic wastes (IOM3, 2020).

In the second stage of recycling, collected waste in the mixed form is taken to material processing centres to be sorted, where separate waste plastics from the other wastes such as glass, metal, paper or cardboard. Additionally, plastic waste can be separated into types of plastics. Although plastics are commonly based on petrochemical materials, they are produced in different chemical combinations and structures according to the sought capabilities for the application purpose. The variation of plastics that are suitable for being remelted and reused (namely thermoplastics) are mainly categorised in seven as described in the following table:

Symbol	Polymer	Common Uses	Properties	Recyclable?
1 PETE	Polyethylene terephthalate	Plastic bottles (water, soft drinks, Cooking oil)	Clear, strong and lightweight	Yes; widely recycled
2 HDPE	High-density Polyethylene 3	Milk containers, cleaning agents, Shampoo bottles, Bleach bottles	Stiff and hardwearing; hard to breakdown in sunlight	Yes; widely recycled
3 PVC	Polyvinyl chloride 4	Plastic piping, Vinyl flooring, cabling insulation, Roof sheeting	Can be rigid or soft via plasticizers; used in construction, healthcare, electronics	Often not recyclable due to chemical properties; check local recycling
4 LDPE	Low-density Polyethylene 2	Plastic bags, Food wrapping (e.g. bread, fruit, vegetables)	Lightweight, low-cost, versatile; fails under mechanical and thermal stress	No; failure under stress makes it hard to recycle
5 PP	Polypropylene 1 Demand in the EU	Bottle lids, food tubs, furniture, houseware, medical, rope, automobile	Tough and resistant; effective barrier against water and chemicals	Often not recyclable; available in some locations; check local recycling
6 PS	Polystyrene	Food takeaway container, plastic cutlery, egg tray	Lightweight; structurally weak; easily dispersed	No; rarely recycled but check local recycling
7 OTHER	Other plastics (e.g. acrylic, polycarbonate, polylactic fibres)	Water cooler bottles, baby cups, fiberglass	Diverse in nature with various properties	No; diversity of materials risks contamination of recycling

Table 2 Main 7 types of thermoplastics (Klemeš et al., 2020)

As the table describes, the chemical characteristics of the plastic types also impact their recyclability and their eligibility for various recycling processes.

After being separated into the types, plastics are taken into the various recycling processes. Among them, the most conventional technique is mechanical recycling. Plastic waste materials are initially transformed into smaller pieces via activities such as drawing, cutting, shredding and grinding. Next, granulated flakes of plastics are washed and dried. In the last step, they are melted and extruded to produce the pellets which will be used as the recycled plastics base materials. Finally, the pellets are baled and shipped to the manufacturers.

Mechanical recycling can also be executed at the sites of manufacturers and the scrap materials are immediately recycled into the base material form. This action is also named re-extrusion or closed-loop recycling.

Another method of recycling is the chemical recycling of plastics, which can also be named 'advanced recycling'. In this method, plastics are chemically transformed back into their base constituents (into the form of oil, fuel or building blocks of new plastics) by external impacts such as heat, pressure, oxygen depletion, catalysts or solvent. It is also considered a complementary step of mechanical recycling, as it enables the recycling of materials that are hard or impossible to recycle with the conventional mechanical methods (BPF, 2021b). There are three main types of chemical recycling: purification which is based on the separation of the polymer from its additives and contaminants; depolymerisation (named also as chemolysis or solvolysis) which is essentially the reverse of polymerisation and yields single-monomer or short polymer fragments (i.e., oligomers) via the catalysing techniques such as methanolysis, glycolysis, alcoholysis and hydrolysis; and lastly the feedstock recycling (named also thermolysis or thermal cracking) which uses thermal processes such as pyrolysis or gasification to convert the polymers into petrochemical-type feedstock for new polymer production (BPF, 2021b).

Finally, the last option of recycling for plastics before ending up in landfill is the incineration of the waste for energy recovery purposes. Since this method produces energy instead of practically keeping the material in circulation, it is not accepted as a recycling method by some field authorities. Nevertheless, this lack of consensus does not decrease the importance of energy-from-waste initiatives, as it is the last step for the plastic waste that could not be recycled via the preceding techniques.

At the end of the recycling processes, depending on the applied recycling technique, different recyclate materials are produced. Mechanically recycled materials, for example, are tagged with an 'r', resembling the recycling, such as rPET, rPP, rHDPE. Chemical recycling, on the other hand, produces various base materials depending on the type of chemical recycling. While pyrolysis, for example, produces Naphtha, Distillate Gas Oil, Heavy Gas Oil, Heavy Wax Residue, glycolysis produces BHET and PLA. These base materials are utilised for the production of new plastic products.

Besides outlet material types, recyclates also differ according to their application capabilities. Some recycling activities produce materials that have equal or higher characteristics than the recycled waste they are produced from. This recycling is also called upcycling. The most prominent example of upcycling is the chemical recycling activities, which produce virgin-quality base materials that will have similar characteristics as virgin petrochemical-based plastics. Another example is the mechanical recycling activities that use clean waste and produce recycled products to be used for the same purposes, such as the HDPE milk bottles that have highly efficient recycling capabilities. Food-grade recycling is the most prominent aspect of upcycling, and raises the interest of both academics and practitioners who aim to extend the lifetime of recycled materials in higher quality food-grade applications. In contrast to this goal, plastics may not keep their original quality as they are recycled especially mechanically. This is mainly a result of the mechanical processes such as granulation and shredding, which reduce the length of the polymer chain of the recyclates as well as the strength of the bounds among the monomers. In these situations, recyclates are used for lower quality applications such as outdoor furniture, sustainable building blocks, playground or athletic court ground floor material, or even as road-making materials. These applications are hence called downcycling as the opposite of the first category, upcycling (Kahlert and Bening, 2020; BPF, 2021a).

Methodology

As depicted in the literature review section, plastics have a highly complex recycling roadmap depending on various dynamics such as their inherent chemical characteristics and post-consumption situations. While these dynamics determine the recycling journey of a plastics waste, they also diversify the challenges and opportunities in this route. This complexity of the nature of plastics, and the ambiguity of the sectoral challenges and opportunities require an in-depth exploratory study to bring the required clarity to the field. This study, therefore, has been designed as a case study (Yin, 2003) and focused on the North East of England plastics recycling supply chains. North East of England is a region enriched with an intense investment in processing and petrochemical industries. Since plastics production is also an important part of these industries, the region also holds a prominent potential for the recycling of plastics, which can be seen in the already existing activities. To identify the existing status of the sector in the region as well as its development paths with potential opportunities and counteractions to the challenges, this study has pursued the following objectives:

- Identifying the sector actors by mapping the supply chain,
- Identifying their capabilities and requirements by conducting competence profiling activities,
- Identifying the challenges and risks as well as development opportunities and risks,
- Customising the plastics recycling supply chains by their differing characteristics

In the first step of the process to achieve these objectives, companies acting in the region as a part of the regional plastics recycling supply network were identified together with their roles. To do so, a four-step procedure was followed: determination of the plastics recycling supply chain echelons, identification of the potential regional companies, elimination of companies in line with their relevance, and snowballing of the further related companies throughout the project.

To begin with, it is needed to understand the roles of the companies in plastics recycling supply chains. Following the plastics recycling supply chain model and the waste hierarchy framework, the following four categories were constructed to set the boundaries of this project:

- main recycling companies,
- suppliers of the plastics waste,
- existing/potential customers of recyclates, and
- supportive companies.

The focus on the recycling companies was limited to the North East of England. Consideration for the other categories, on the other hand, was kept more flexible to include companies from the UK and worldwide since the flow of plastic waste can be difficult to limit and the services of the supportive companies can be exempt from the geographical boundaries.

In the second step, the repository of the North East of England Process Industry Cluster (NEPIC) was utilised as the main data source. NEPIC is a not-for-profit organisation that supports the needs and interests of the chemical-processing sector in the North East of England by identifying opportunities, facilitating connections and promoting collaborations (NEPIC, 2022). NEPIC's database initially provided 103 companies to consider in the project, which can be broken down into the identified categories as 34 main recyclers, 28 suppliers/buyers of plastics waste or recyclates and 41 supportive companies. In the following phase, an internal evaluation was done throughout the identified company list and the total number decreased to 56, respectively for each category 24, 14, and 18.

The data collection phase of the project started with this revised list with company interviews and secondary data where accessible. During this stage, additional companies were also identified as the connection of the existing participating companies. Conclusively, the ultimate list of project participant companies was completed with a total of 40.

The interviews conducted with the participating companies aimed to understand the recycling status of the region. Four main perspectives that were included in the interviews are:

- flow of the different plastic types,
- recycling process capabilities of the companies,
- challenges they encountered and
- opportunities for the sector in the region.

Collected information was analysed via a combination of the techniques. Initially, the plastics recycling supply chains were mapped to illustrate the regional plastics waste flow. As its complement, a competence profiling technique was applied to identify their capabilities as well as the challenges and opportunities they face. Lastly, identified supply chains were categorised via a supply chain customisation matrix that diversifies the supply chains according to the plastic types they recycle and their recycling techniques.

To conclude the project, findings were shared with the participating companies through a workshop, where they ranked the accumulated challenges and opportunities. Additionally, further actions were identified in the workshop for the development of the plastics recycling industry within the region.

Results

Flow of the plastic waste

In the earlier sections, seven main types of plastics were identified comparatively according to their recyclability. A similar trend was also observed in the recycling sector of the region.

To begin with, PET was expectedly found as one of the most recycled plastics in the region with three waste providers in small and medium amounts. Besides the main PET waste, the region also has some waste of PETG derivatives and multiple polyester waste providers. Regarding HDPE, LDPE and PP, there are two main single-stream waste sources that provide the waste of all these plastics types collectively. Besides, two other companies provide PP waste in the region. In contrast to commonly recycling plastic types, waste of other types is not separately provided as much in the region. While PVC waste can only be found in a single company, there is not any identified company for the PS waste. Apart from the single and separated waste provision, most of the plastic waste in the region is provided in the mixed form by multiple waste producers including both industrial and consumer waste sources. Lastly, the region harbours some other types of plastic waste such as acrylic, PEEK, TPE and Polycarbonate.

Going through various recycling processes, entrant waste plastics end up in four main destinations: food-grade recyclates, non-food-grade recyclates, energy and landfill. Among the food-grade recyclates, there are naphtha, distillate gas oil, heavy gas oil, and heavy wax residue that comes from chemical recycling (hydrocracking); and PLA and BHET from hydrolysis and glycolysis recycling methods. In comparison to that, the region has more non-food-grade outputs expectedly, which varies from the mechanical recycling recyclates such as rPET, rHDPE and rPP. Third, waste plastics are turned into energy by some companies via gasification and incineration techniques.

Recycling process capabilities

North East of England harbours companies with process capabilities for all stages of plastics recycling. Starting with the collection phase, seven companies conduct waste collection activities including both industrial and post-consumer waste in single, separated and mixed forms of waste. While five of these companies have also the capability to sort the mixed waste before processing in the material recovery centres, one company can collect polyester waste in a separated stream from the various channels using their own drop points.

Regarding the actual processing stages, the region has multiple firms with varying capabilities. Among the participating companies of the project, the seven have mechanical recycling capabilities. At this point, it is also important to mention there is one company with the closed-loop recycling capability in acrylic recycling. Chemical recycling, on the other hand, has further potential in the region with eight companies with varying chemical recycling capabilities such as hydrocracking of flexible, soft plastics that generally go to incineration, hydrolysis, repolymerisation, glycolysis and pyrolysis.

For the occasions where plastics cannot be recycled but utilised for energy production, there are five regional companies with suitable capabilities such as gasification and incineration.

Lastly, the potential of the region for plastics recycling has also covered the local and other companies that have supportive capabilities for plastics recycling. The context of support can be categorised under six main groups: Turnkey plant preparation and maintenance, waste management consultancy, measurement and auditing support, waste brokership, material support and logistics.

As depicted in the previous chapter, the first two objectives of this study were to identify the sector actors and their capabilities. By identifying the flow of plastics in the region and the recycling processes applied by the regional actors in plastics recycling supply chains, these objectives were accomplished. Furthermore, by the applied supply chain map and competence profiling techniques an interactive 'Plastics Waste Flow' tool has been developed for the region, which enables the visual analysis of the waste flow of different plastic types throughout the sectoral companies of the region that apply differing recycling techniques with various capabilities. The plastics waste flow and the map of the regional plastics recycling supply network allow users to navigate through the recycling activities and the waste flows by clicking on the boxes and the lines. The main screen of the tool is presented in Figure 2 below.

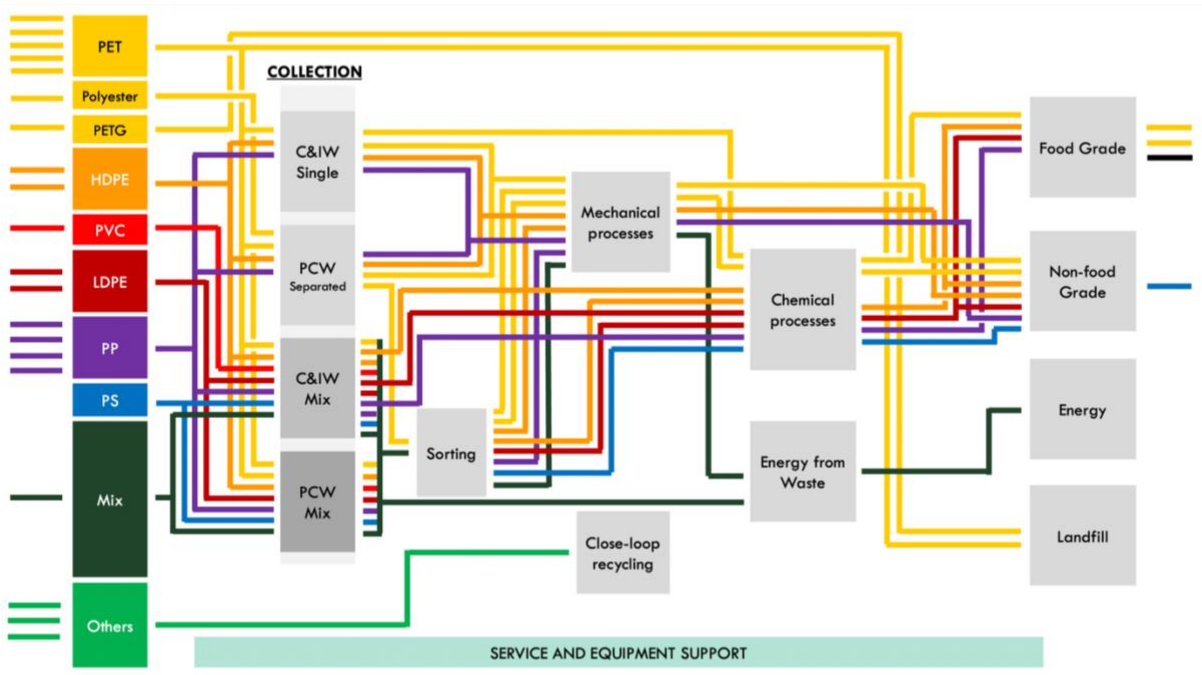


Figure 2 Main screen of the plastics waste flow tool

Challenges of Plastics Recycling

Activities toward plastics recycling are steadily increasing along with public awareness and changing policies. In line with this interest, recycling capabilities are also developing, however, the desired level of circularity for plastics is not close yet since the development speed is impacted by various obstacles. Challenges faced in the plastics recycling sector can be grouped under seven main categories.

1. Scarcity of the collected recyclable waste: Since there is a difference in the recyclability of the plastic types, plastics that are easy to recycle such as PET, HDPE

and PP are collected relatively more than other types such as LDPE, PS and PVC. Besides, the clarity of the collected waste also impacts the efficiency of recycling. While waste clarity decreases the recycling cost, it also enables the production of high-quality output. Therefore, recycling companies prefer clean waste, however, the collection of clean material in a sustainable flow is not easily managed.

2. Mix materials, contamination and impurities: Collection of waste in a mixed form is a persisting challenge for the recycling sector as mixed waste requires a complex process of sorting and separating. These processes become harder when the waste plastics have contamination from their previous usage. On top of that, plastics may have impurities depending on the application purpose of the material such as lamination, metals, inks, adhesives, pigments, blending, additives and printing. These need to be separated from the base constituents of plastics before the recycling process. One specific aspect regarding the sorting difficulties is the black plastics. They cannot be detected by most of the sorting techniques, and therefore they require some additional workload to be prepared for the recycling stage.

3. Technical difficulties: Comprising multiple stages, recycling is a complex and challenging activity per se. However, it also gets more difficult from some specific aspects. First, companies can have capacity efficiency problems when they cannot reach the right quality of plastic waste for recycling in the required amount. This is especially experienced in mechanical recycling plants. On the other hand, the capacity problem shows itself in chemical recycling in a form of the scalability challenge as a result of the low financial viability of the commonly applied chemical methods. Adverse environmental impacts of some chemical recycling methods such as pyrolysis and gasification also some other concerns regarding its broad application in the recycling sector.

4. Output quality: When plastics are downcycled via mechanical recycling, they degrade because of multiple reasons such as viscosity reduction and shortened molecular chains. Therefore, to enable the material quality of the original material, recycled plastics may be unsuitable.

5. Economic efficiency of the virgin resins: Another challenge of recycling is its relatively higher cost in comparison to the petrochemical-based virgin plastic resins. While the cost of subsequent recycling processes adds up to the pricing of recyclates, seasonal reduction in the price of petroleum enlarges the gap between the prices of virgin and recycled plastics. This, in the end, causes firms to refrain from using recycled plastics in higher proportions.

6. Limited transparency of recycling: As a side effect of management of recycling processes in bulk form, the sector suffers from a lack of transparency regarding the lifecycle of the materials. Considering the increasing awareness towards sustainability and circular economy in the society and business industries, recycling companies encounter an increasing number of waste providing companies that enquire about the momentous status of their waste where applicable. Another relevant challenge is being experienced when the plastic waste is exported and its tracking is restricted in terms of the end destination and the current form of the waste. Throughout the plastics recycling supply chains, another transparency issue that companies find challenging is the limited knowledge regarding the regional

capabilities including multiple aspects such as existing potential waste sources that could provide plastics waste with higher recyclability in lower effort and investment, existing potential capabilities of the nearby recycling companies that could provide further solutions to the waste problems, or the existing potential users of the recyclate materials. Lastly, it is also crucial to state the relevant measurement issue. Since transparency is not achieved throughout the recycling supply chains, data regarding the recycling efficiency, total economic cost or the indirect environmental impacts cannot be collated to provide a holistic life cycle analysis.

7. COVID-19: The pandemic of COVID has brought some critical challenges to the recycling sector and sustainability. Due to the hygiene and contagion risks, people refrained from using multiple-use materials including plastics and on the opposite, single-use plastics have gained more interest. In addition, rocketing numbers of medical equipment used for the management of the pandemic -starting from individual masks to test kits and vaccine materials, have also produced potentially infected plastic waste that is risky to recycle for high-quality applications. Therefore, in sum, the pandemic has caused an accumulation of plastic waste that is risky to recycle via conventional methods.

Opportunities in the Sector

North East of England's development potential in plastics recycling becomes more critical considering the future opportunities in the sector. This project has identified four opportunistic perspectives that can bring further benefits to the companies alongside the enhancement of the plastics recycling sector: compatibility to the standards and legislation, collaboration potentials, innovation, and the advantages of the freeport in the region.

Legislations regarding the recycling of plastics have been based on the applications of Packaging Recovery Note (PRN) and Packaging Export Recovery Note (PERN) policies. Although they aimed to bring further transparency to the recycling of plastics, they also had drawbacks and required improvements. To incentivise plastics recycling in the UK, additional legislations are planned to be implemented in the coming years, namely 'Deposit Return Scheme (DRS)' from 2022 (Scotland only) and 2023 (England, Wales, and Northern Ireland), 'Extended Producer Responsibility (EPR)' in 2023 (UK) and 'Plastic Packaging Tax (PPT)' in 2023 (UK). These regulations aim to increase the usage of recycled feedstock in plastic production. In other words, the need for recycled plastics and hence plastic recycling sector will increase simultaneously in due course.

The second aspect that companies can tap into the further improvements in plastic recycling is the potential collaborative activities. As described in the previous sections, plastic recycling supply chains are composed of complex structures with specific capability requirements. Therefore, to enhance the efficiency of recycling and marginal productivity for the companies, there is an increased need for collaborative endaveours. Recent and existing funds and incentives for the collaborative project in the region and the UK also show the importance of collaboration in the advancement of the sector.

The third aspect, innovation, is also closely connected to challenges of the sector. Among the innovations to develop the sector are the improved collection and segregation schemes, recycling processes -especially in the novel technologies in sorting the waste and chemical recycling to upscale the recycling amount, and design of further applications for the recyclates.

Lastly, the announcement of the Teesside Freeport can also be an opportunity for plastics recycling in the region. As mentioned in the boundaries of this project, company capabilities can be developed within the geographical region however, the flow of plastic waste is boundary-free. In line with this, plastic waste -sorted and baled form of the waste- and recyclates are transported within and out of the country for the current situation. Together with the development of the sector in the region in due course, the proposed freeport is also considered to facilitate the flow of materials for further benefits.

Discussions

Collaboration among the companies was previously presented as an opportunity for the further development of the supply chain recycling sector in the North East of England. Enlarging the scope, a holistic integration would be key to transforming the region into a leading example in plastics recycling for the UK and even for the EU. To discover the potential opportunities to capture and challenges to overcome, this project applies a supply chain customisation approach to unleash the impacts of differences in products and processes.

Customisation of the companies and the associated supply chains have been based on the categorisation of Tsinopoulos and Mena (2015). To categorise the supply chains, the authors identify two main factors that diversify the activities of the companies: product familiarity and process complexity. Adopting this approach, this project has categorised the companies in plastics recycling supply chains according to the level of process complexity of applied recycling processes and the familiarity of the plastic types they recycle. The spectrum of processes, therefore, ranges from chemical to mechanical recycling as a result of the complexity of these processes. Types of plastics, likewise, range from PET to various niche plastics, based on their recyclability. Combining these two spectrums in a single matrix, four supply chain models are identified: Customised, Ramp up, Recurring and Coordinated. These models identify the collaboration opportunities among the companies depending on their capabilities, while they also bring insights about the potential challenges and further business opportunities they may face following the study of Mogre et al. (2016).

Starting with the lower ends of both axes, the ‘Customised’ integration model suits best the firms that recycle the rarely recycled waste types in low volumes. In this model, firms focus on understanding the market requirements and supplier capabilities to shape their integration activities and sustain their competitive advantage. At the action level, they can integrate the potential waste customers at the early stages of the relationship without drowning in the details of technical requirements until later in the development cycle. In the region, companies recycling plastics with lower recyclability ratios such as PS, PVC, PMMA, Polyester and other special and niche plastics by using complex techniques with low output volume and standardisation such as chemical recycling or sorting and separation activities can adopt these integration models. In this model, one specific challenge firms may face is the immaturity of recycling techniques, especially in chemical recycling and sorting & separating technologies. While the developments in the area can be adopted to bring direct solutions for such difficulties, research around the recyclability of COVID-related and other medical wastes may also bring further opportunities.

The second integration model, ‘Ramp up’, suits the firms that recycle similar plastic types with lower recyclability potential by more conventional and simple processes in higher volumes and standardisation. These processes can include waste collection schemes, energy from waste activities and mechanical recycling. Integration activities in this model may focus on the development of the systems and processes that will enable the prompt delivery of new products to the customers. The supplier is integrated across the new product development process, while the customer’s integration is left to the product testing stage. Firms in the ‘Ramp up’ integration model can tap into the opportunities such as innovative recycling outlets of materials either difficult to recycle or non-recyclable.

The third integration model, ‘Recurring’, is based on the recycling of familiar waste such as PET, HDPE, LDPE and PP by techniques of higher complexity and lower volumes and standardisation. Integration activities focus mainly on improvements of existing products to answer the increasing need for food-grade or high-quality recyclates. While waste suppliers may provide cost improvement ideas and detailed information of their capabilities early in the new development cycle, customers of recyclates may be included to provide information regarding the required modifications in their expectations and technical details. While the firms in this integration model can get the benefit from developing recycling techniques and technologies, they may be challenged by the difficulty of collecting recyclable material in adequate quality.

Lastly, a more ‘Coordinated’ integration model can be among the firms that recycle those aforementioned familiar plastic types by using more conventional techniques with high volumes of recycling and standardisation. This integration aims to meet the continuous requirement for recyclates in the market. In this collaboration model, activities focus on cost reduction. Supplier integration is limited and focused more on cost reduction through process improvements, while customer integration is focused on getting feedback, especially if there is a change in their needs. The main challenges for firms’ integration in this model are the cost of recycling, economic efficiency against virgin resin and loss in material quality in mechanical recycling. Firms may also have difficulty in finding a consistent flow of high-quality waste to sustain their capacity, however, the introduction of the freeport in the region may bring opportunities in this lead.

Conclusion

The project initially targeted to unearth the opportunities of supply chain integration for the plastics recycling industry of the North East of England. To reach this ultimate goal, it has first mapped the nodes in the plastics recycling supply network of the region. To complete its impact, the supply network was enhanced with the capabilities of the companies in these nodes and the end-to-end flow of plastic waste among them. While these applications put forward the state of the field and industry in the region, it also brings transparency regarding the supply chain entities and capabilities. Considering it was one of the challenges faced by the sectoral firms, this project is believed to bring solutions in that lead.

The project takes one step further as well in terms of impact by elaborating the models of integration for proposed spectrums of plastic waste type and recycling processes. Utilising the supply network map, firms can identify their and potential partners’ position as well as the potential capability and challenges. Guidance for integration categories can be another tool to use in the operationalisation of the integration strategies.

Lastly, the last phase of the project is actuated via a discussion and dissemination workshop that hosted the participants of the project as well as some other interested sector practitioners. While the workshop primarily focused on disseminating the findings, it also assisted in networking among the participants.

The workshop has also guided the next steps of this project lead. Initially, the region requires a special interest group for the operationalisation of the proposed supply network and plastic waste flow map, and the management of the existing and future challenges’ solutions and opportunities’ capture. Another advancement direction is the transformation of the created supply network and plastic waste flow map into an online, real-time interactive form. This transformation can help continuous utilisation of the tool both by the associated firms to facilitate their integration activities and also by the special interest group to provide sustainable development of know-how in the sector.

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