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Recycling options for Derelict Fishing Gear

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Executive Summary

Introduction

As part of the MARELITT Baltic project, WWF Germany has carried out recycling trials with derelict fishing gear (DFG) retrieved from the German Baltic Sea. MARELITT Baltic is an EU-funded INTERREG Baltic Sea region project with the aim to mitigate the impact of DFG on the Baltic Sea marine environment. WWF Germany leads work package 4 (WP4) which results in recommendations for the handling and processing of retrieved DFG in the form of a DFG treatment scheme. The scheme can then be adapted to other countries and marine ecoregions where lost fishing gear is retrieved and collected in fishing harbours.

MARELITT Baltic WP4 covers

- a survey of harbour infrastructure (led by Keep the Estonian Sea Tidy (KEST), M. Press 2018)
- handling and pre-processing of retrieved DFG in ports (KEST, in prep.)
- a survey of logistic requirements and economic viability of DFG recycling (WWF Germany)
- recycling trials to evaluate the technical feasibility (WWF Germany, this report).

All of these aspects feed into the DFG treatment scheme. As such, the treatment scheme provides recommendations for future DFG retrieval operations to develop a pathway for DFG recycling that can be applied also in the framework of the EU plastics strategy.

This report on technical feasibility describes in detail the results of all DFG recycling trials and the physical and chemical properties derived to evaluate the material quality of lost fishing gears retrieved from the Baltic Sea. The aim of this report is to provide a baseline of technical feasibility and processing options for retrieved fishing gear. The analyses and trials carried out lead to recommendations of how retrieved fishing gear can be treated to enter the value and recycling chain.

Recycling

With the aim to evaluate the potential of lost fishing gear for the plastics value chain, the focus was placed on the two predominant waste management pathways: material recycling and thermal processing. A wide range of experiments from pre-processing, shredding and fibre washing to high-temperature thermal polymer evaporation was carried out. Most contacts to companies dealing with the preparation of materials for recycling, the chemical analysis, and the thermal processing were provided by MARELITT Baltic Associated Partner Tönsmeier Entsorgungs GmbH, one of the largest recycling and waste management companies in Germany. Pre-processing of all materials was conducted with participation of WWF Germany in the technology centre of Vecoplan AG in Bad Marienberg, Germany. Vecoplan AG builds industrial shredders for waste processing, and the technology testing included industrial washing and density separation stages. Material recycling trials were carried out at the Technical University of Magdeburg-Stendal by Prof. Dr. Gilian Gerke and her team, who has one of the rare research groups with experience in the field of DFG processing. The material recycling trials were conducted by Dr. Gunter Weißbach as the chief laboratory scientist, who had worked with ropes and nets from sea-based samples before. Thermal processing included a laboratory-scale pyrolysis experiment carried out by Thomas Horst and Johann Hee at the Technical University of Aachen in the Unit of Technologies of Fuels (TEER) led by Prof. Dr. Peter Quicker. A high-temperature evaporation process termed "steam reforming" was conducted at EXOY's test reactor in Freienbach, Switzerland. The major results of the physical, mechanical and chemical analysis and all processing steps are summarised below.

2.1 Preparation for recycling

When retrieved from the sea, DFG is a highly mixed material that contains metal anchors, chains, organic matter such as mussels and dead fish and other marine litter as well as nets, ropes, float and sink lines. Between two and four handling stages are necessary to prepare retrieved fishing gear for either thermal or material recycling. All processing trials were conducted at Vecoplan AG's technology testing centre in Bad Marienberg, Germany.

1) First, pre-processing is required to remove large metal fragments, rocks and other disturbing substances that cause severe wear on shredding blades or other cutting devices. The separation of DFG into ropes, trawl netting and gillnets is required prior to shredding when aiming for material recycling.

2) In the second processing stage, the material is shredded. After this step a separation of fibres into individual fractions is technically challenging.

3) Density separation: DFG retrieved from the sea is typically heavily entangled, such that float and sink lines cannot be manually removed. The lead weights in gillnet sink lines cause toxic contamination and can render an entire fibre batch unusable. Density separation in saline solution facilitates the removal of heavier lead fragments and sediments from the lighter polymer fibres. The floating fibre fraction can be extracted from the surface of the solution. In practical trials, the fluffiness of the fibres caused fine-grained sediments and small lead fragments to be trapped. Density separation alone did therefore not result in a clean separation of fibres from disturbing substances. In a second density separation stage, the extraction of high-density polyamide (PA6) from low-density polyolefins (polypropylene PP, polyethylene PE) was tested. In fresh water, the PA6 fibres should sink while PP/PE fibres are expected to float. Each fraction can in principle be extracted either from the surface or from the separation tank floor. As in the first density separation stage, the fluffiness of the PA fibres prohibited a clean separation, and residual contamination was present in all fractions. On the other hand, density separation substantially reduced the lead contamination by approximately a factor of ten. Sediments that would otherwise have further reduced the quality of the washing process were also removed. Density separation is thus highly recommended when fibres are prepared for material recycling.

4) Fibre washing: Different types of industrial washing systems are available on the market. At Vecoplan's technology centre, a Hydrodyn friction washer was available. Fibres are diluted with a washing liquid resulting in a 3% solid material concentration liquid. This liquid is pressed through two counter-rotating discs with grooves. The rotation causes a centrifugal force that guides fibres to migrate outwards along the grooves. The friction between the discs effectively expells sediments and other organic particles with the washing liquid. Washing improved the fibre quality visibly. However, the fluffiness of the material still caused small organic (wood) and lead fragments to remain mixed into most of the input materials. The best washing results were achieved with pre-sorted net and rope fractions of almost uniform quality and polymer type.

Recommendations
Pre-processing, i.e. the removal of large metal pieces such as anchors, chains, cables and larger rocks, is essential for all further processing steps. Pre-processing can best be implemented directly in the landing harbour to avoid unnecessary weight during transport. Shredding with industrial shredders is unproblematic in case the shredder contains a safety-stop with back rotation. Without a safety-stop mechanism and in small-scale cutting mills fibres cause system blocking and extensive motor heating and machine wear. Density separation should be considered a necessary step to minimise contamination with residual sediments and toxic lead fragments. Industrial friction washing works well for monofilament fibres, but is less efficient for woven fibres (trawl netting). Separation of individual rope and net types is beneficial for all processing stages and is required to obtain comparably uniform samples for material recycling.

2.2 Chemical analysis

A detailed chemical analysis was conducted by MAKSC GmbH on five different samples of retrieved DFG. The chemical analysis confirmed the four expected dominant polymer types in fishing gear: PA6 and PET as high-density polymers, and PP, PE as polyolefins. None of the five analysed samples resulted in a pure single-type polymer fraction. All samples, including the PA6-dominated gillnet samples and the PET-dominated ropes, showed contamination with polyolefins. The analysis of hazardous substances followed the EU REACH protocol and revealed high lead concentrations of up to 360 ppm, a factor of four higher than the limit in the EU packaging directive. Initial fibre concentrations were as high as 3 grams per kg of shredded gillnet material. Fibre processing and density separation have reduced the initial lead concentration in the gillnet-dominated sample by a factor of ten. While the high lead concentrations are known to originate from sink lines, the origina of an enhanced chlorine concentration in two samples could not be traced. Hence granulation and recycling of DFG into consumer goods is restricted to DFG fractions without potential toxic contamination.

Recommendations
Lead lines should be removed as far as possible to reduce toxicity in the final fibre batches. The better the level of pre-sorting, the higher the resulting material quality in terms of uniform polymer content and reduced contamination with substances listed under REACH. A REACH analysis prior to granulation for material recycling is highly recommended.

2.3 Physical and mechanical analysis

A detailed analysis of the physical and mechanical properties was commissioned to allow for comparison of DFG recyclates with other recyclates on the market. Tensile strengths and melting properties (melt flow indices) are found to be comparable to recyclates generated from end-of-life fishing nets. Elongation at breaking strength and impact strength are significantly reduced in DFG test specimen, which is likely a direct consequence of residual impurities that could not be completely removed from fibres retrieved from the seafloor. A lower breaking and impact strength of the DFG test specimen are expected to result in less durable products, which might limit injection moulding and other applications.

Recommendations
Pre-sorting of rope and net samples is essential to ensure material quality. Several washing stages will facilitate the removal of impurities resulting in more uniform material properties and should be considered in larger-scale processing operations in the future.

Recycling trials

Thermal processing and material recycling were tested with gillnet-dominated input material. This type of material was considered the most challenging because of the contamination with lead from sink lines, sediments, and organic matter trapped in the monofilament fibres. For comparison reasons and to address the technical challenges involved in DFG recycling, the same type of input material was used for all trials.

3.1 Thermal processing

3.1.1 Pyrolysis

Pyrolysis of polymers was conducted at 500-700°C in the laboratory pyrolysis oven in the *Unit of Technology of Fuels (Technologie der Energierohstoffe TEER)* at the Technical University of Aachen (RWTH). The solid residue contained a large ash and coke fraction, implying that depolimerisation leads to a solid residue of about 66% of the input material weight at the comparably low temperatures used in pyrolysis reactors. Higher-temperature techniques such as steam reforming operating at temperatures above 1000°C with a high humidity level (see below) allow for almost-complete vaporisation and conversion of organic material inlcuding polymers into carbon-binding emission gases (CH_4, CO_2). Pyrolysis operates at too low temperatures, pressures and with dry material input which does not allow for vaporisation of the carbon content. The coke and ash residue requires further extraction of lead and metals for metal recycling.

One strong argument for pyrolysis brought forth in the context of marine litter is that the liquid condensate could potentially be used as ship engine fuel to sustain operations in the high seas. In our trials, the condensate return was very low with fractions of only 2-5% of the total input by weight. At lower temperatures of 500-600°C, the condensate had a wax-like consistency rendering it unpourable and hence unusable as fuel without prior heating, as is the case for crude oil. The condensate had the lowest viscosity at the highest temperature of 700°C and the required pourability for use as fuel without a prior heating stage. In its denser and more viscous form, the condensate may resemble crude oil, and vessel engines running on crude oil might be able to cope with such a fuel input. However, the chemical composition of condensate originating from mixed input materials is expected to contain contaminants and might not fulfil even the less restrictive DIN regulations for ship engine fuels. The chemical composition was not tested for further conclusion on using condensate from DFG as engine fuel, and the return was still low at higher temperatures resulting in a fuel fraction of at most 5% of the input weight.

A possible further limitation of pyrolysis in mixed polymer samples and especially in the case of DFG is the fact that PA6 vaporisation at low temperatures can lead to highly toxic hydrocyanic acid emissions. While toxicity in emissions was not sampled, this limitation might impede the use of pyrolysis in large-scale DFG and marine litter applications. A subsequent gas processing stage can technically remove the toxic content from the pyrolysis gas, but this requires a more complex and expensive system.

3.1.2 Steam reforming ("hydrolysis")

Steam reforming is a high-temperature vaporisation technique that involves water being split into hydrogen and oxygen atoms in order to generate a synthetic gas with a substantial hydrogen content. The energy contained in polymers or other forms of organic waste is used to split the strong hydrogen bonds of water molecules to generate the synthetic gas. Residual carbon is bound either to oxygen forming CO_2 or to hydrogen forming CH_4, such that the remaining solid residue contains mostly metal fragments and sediments. A heavily contaminated gillnet sample was processed in EXOY's ultrahigh-temperature steam reforming reactor at 1100°C. The 312kg of gillnet material led to a solid residue of 151kg dominated by sediments and lead. The lead fraction in the residue was more than 42%, implying a lead contamination of at least 20% in the original material. The vaporisation resulted in a synthetic gas with 48% hydrogen content and CO, CO_2 and CH_4 as the other dominant components. In contrast to lower-temperature pyrolysis where organic molecule disintegration leads to a larger ash and coke residue and the formation of hydrocyanic acid in the presence of polyamide molecules, steam reforming does not result in toxic emissions. The solid residue has virtually no coke content and is composed mainly of steel/iron powder, re-condensed lead fragments, residual sediments, and a small amount of sludge. Because of its melting and recondensation and the low coke residue, lead can easily be extracted for recycling, hence avoiding gillnet-dominated DFG having to be disposed of as hazardous waste. The synthetic gas can be exploited either for direct energy generation through a turbine or as a source of hydrogen for fuel cells. With a hydrogen fraction 10-20 times increased as compared to natural gas, hydrogen extraction should be highly efficient from the resulting synthetic gas. In the case the synthetic gas cannot be exploited or combusted, the CH_4 content as a strong greenhouse gas has to be captured to avoid negative effects as a climate change driver if this technique is used on industrial scales.

Recommendations on thermal processing
Hydrolysis is recommended for DFG processing when materials are mixed and lead and/or organic contamination is high. Extraction of lead allows for metal recycling rather than depositing DFG as hazardous waste. The hydrogen-rich synthetic energy gas generated from polymer disintegration provides a more efficient form of energy-reuse of DFG polymers than heat extraction in a classical thermal waste incineration plant. Additional benefits of steam reforming are the low processing effort and costs. Only pre-extraction of large metal and rock items is required prior to shredding to 20-30mm fibre length. More elaborate processing stages such as density separation or fibre washing are not necessary prior to thermal processing.

3.2 Material recycling

Material recycling of density-separated and washed fibres was attempted for the same gillnet-dominated samples used as input for thermal processing experiments. The required efforts in terms of further processing steps and manual labour could therefore directly be compared. The experiments were carried out at the Water and Circular Economy Resources Centre of the Technical University of Magdeburg-Stendal. The chemical and mechanical analyses confirmed the results by the external polymer laboratory (Sec. 2). Mechanical properties suggest the polymer components could be material recycled under the prerequisite that a better separation and washing technology can be developed. Residual fine-grained sediments were observed to cause extensive wear on cutting and grinding equipment. Material recycling of gillnet-dominated samples proved very challenging because of the residual contamination with lead and wood fragments, sediments, and the overall polymer mix. The dominant material PA6 was mixed with PET, PP and PE disturbances. The polymer mix implies a wide range of melting points from 140 to 260°C. Less thermally stable low-density polyolefins PP and PE would begin to coke at the temperatures required to melt and regranulate PA6 and PET. The resulting recyclates would contain ash, leading to a brittle output material. Hence extrusion with the mixed gillnet polymer material cannot be recommended. At Hochschule Magdeburg-Stendal, the fibres were fine-ground to different lengths and exposed to additional washing and density separation experiments. Friction washing had also not been capable of removing tiny lead fragments with up to 2-3mm sizes trapped in small, fluffy PA6 fibre compounds. In addition to lead, small wood and organic fragments are also trapped as a consequence of the structure of the shredded gillnet material that contains loops and knots even when fine-ground down to a grain size of 1mm. In order to evaluate the regranulation potential further, the material was hot-pressed into plates. On these plates, black rubber was identified as a new source of contamination. This rubber contamination can either originate from washing trials carried out in the friction washer before running the DFG trials, or from the DFG itself, e.g. from cable coating that could not be entirely removed. The heated rubber formed porous sections that rendered the pressed plates unstable in these areas. The porous gaps impede production of goods because they provide pre-defined breaking points.

Both rubber and lead contamination will also be problematic in any extrusion and injection moulding process. A high lead fraction leads to a high toxicity and renders gillnet-dominated DFG unsuitable for material recycling into consumer goods. Rubber contamination leads to breaking points that undermine the material stability desired in polymer products.

In summary, the following obstacles to material recycling were encountered in the case of gillnet-dominated DFG samples:

- A high degree of residual contamination with sediments, lead, and organic matter (> 37% by weight)
- Complex multi-component material mix containing at least 4 types of polymers
- Knots, loops and twists are retained down to very small grain sizes of less than 1mm
- Contamination with wood and rubber fragments prohibits uniformity
- Material mix is expected to result in inhomogeneous melts
- Diversity in polymer melting points results in coking of least thermally stable polymers
- Recyclates are expected to have a high degree of brittleness and fracture points
- Lead is spread during processing throughout the samples introducing toxicity
- Lead is spread during processing throughout the samples introducing toxicity

The following minimum requirements can be given as recommendations for gillnet material processing:

- Lead lines have to be removed prior to any processing, in particular prior to shredding and washing of the fibres
- Removing visible contaminants is highly beneficial
- Identifiable different material types should be manually separated
- Lower-density and higher-density polymers have to be separated to avoid technical problems during material extrusion

The material recycling trials showed that gillnet-dominated samples are most difficult to recycle despite the comparably pure polyamide net material. Extensive pre-processing including removal of swim- and sink-lines and trapped waste such as cables would be required to allow for polymer recycling. Even with extensive pre-processing, fine-grained sediments and the fluffy consistency of ground PA fibres might impede material recycling.

Recommendations
For gillnet-dominated, entangled DFG, thermal processing will be more efficient in most cases and is therefore recommended. This situation is different for end-of-life gillnets. As fishermen systematically remove swim- and sink-lines for re-use, the net material is well-suited for recycling as nets are composed of the high-value polymers PA6 and PET. End-of-life fishing nets, while not part of the MARELITT Baltic project and recycling trials, are already recycled into yarn, e.g. by Ecoalf in Spain or Aquafil in Slovenia. The Chilean company Bureo regranulates fishing nets to produce skate boards and other beach items. The Danish company Plastix also hosts a small re-granulation unit for PA6 materials. These efforts, although not directly addressing DFG, support the value chain for gillnets which might help to avoid losses from harbour collection sites into the marine environment.

It has to be noted that recycling of DFG or end-of-life fishing gear does not automatically imply a contribution to the maritime circular economy. This is only the case when the resulting recycling products are designed to have a high recycling potential again after their life span

Conclusions

- The mechanical properties of DFG polymers are comparable to recyclates, and hence suited for recycling.
- Recycling starts at the harbour: Pre-processing is key to prepare DFG for recycling.
- The chemical composition allows for material recycling if materials can be separated during pre-processing. Hazardous substances need to be removed.
- Preparation of DFG for material recycling is technically challenging and elaborate, which leads to high costs for both manual labour and machinery.

- Material recycling is most challenging for gillnet-dominated DFG because of lead contamination from sink lines.
- Large trawl net fragments and ropes provide the easiest recycling samples as they are more readily separated from trapped marine litter such as large metal items, rocks and cables. They also provide more uniform materials that might be used in small-scale production series.
- Thermal processing is recommended for DFG heavily mixed with other wastes and contaminated with lead. Especially for contaminated materials, steam reforming is found to be the best option to exploit the polymer energy content to generate synthetic gas and extract lead for metal recycling.

Given the effort required to recycle DFG, two requirements are identified:

1. Retrieved DFG needs to be incorporated into the existing waste management infrastructure in fisheries harbours (see also Press 2018).
2. Retrieval and pre-processing effort by fishermen, divers or other professionals needs to be financially supported by municipalities or national authorities to establish a DFG value chain.

Examples where functioning value chains are built around end-of-life fishing gear are the Swedish harbour Smögen where the Nordish Fisheries Association collects, sorts, and pre-processes fishing gear for material recycling, and the system of the Norwegian fisheries directorate where yearly clean-up and sorting actions are in place. While DFG is a more complicated and mixed material than end-of-life fishing gear, a general waste stream for fishing gear is the first step towards material recycling. Implementing waste fishing gear collection in harbours is one of the claims in the recently drafted European plastics directive. The MARELITT Baltic recycling study provides a first baseline for the recycling options for derelict and end-of-life fishing gear.

MARELITT Baltic Workshop on (Lost) Fishing Gear Recycling 11-13. April 2018 in Stralsund.

All companies and partners participating in recycling trials presented their results and technologies. In addition to the four MARELITT Baltic partner countries Estonia, Germany, Poland, Sweden, colleagues working against derelict fishing gear all around the world from Norway, Denmark, the UK, Spain, France all the way to Peru and Hong Kong presented their regional efforts to mitigate the ghostfishing problem.

1. Introduction

1.1 MARELITT Baltic project overview – from collection to recycling

The EU INTERREG project MARELITT Baltic[1] has the aim to reduce the impact of abandoned, lost, or otherwise discarded fishing gear, also called derelict fishing gear (DFG) or "ghost nets", on the marine environment of the Baltic Sea. Partners in the four Baltic Sea states Estonia, Germany, Poland and Sweden participate in the effort to search for solutions against the impact of DFG on the marine flora and fauna. The best known impact of DFG is so-called ghost fishing, defined as the unwanted and unselective catch of fish, marine birds and predator species, by lost fishing gear. In the Baltic Sea, this includes threatened species such as Baltic cod as well as harbour porpoises, grey and common seals. A less known impact of DFG on the marine environment is the introduction of plastic waste into the ecosystem. Since the 1960ies, fishing nets are produced using polymer fibres, including polyamide (PA), polyethylene (PE), and polypropylene (PP). In addition, fishing gear and shipping materials found on the seafloor are ropes and metal fragments such as anchors, firehoses, electric cables, and buoys made either from metal hulls or plastics. While polyamide has a higher density than seawater, the polyolefins PE and PP as well as styrofoam (expanded polystyrol) would be expected to float and indeed are attached to fishing gear as swim lines or small float bodies inside the swim line. The contamination with sink-lines containing small lead weights and other metal items, however, cause nets to sink quickly or stay on the seafloor once lost at sea. All of these substances, and in particular plastics and its chemical additives, are considered harmful to the marine environment and potentially to human health (Werner et al. 2016). The long residence time of DFG in the marine environment implies long-term exposure of species and the introduction of potentially hazardous substances into the marine environment.

The forces which break down plastics in the environment are abrasion, UV radiation and oxidation. On the seafloor, fishing nets and ropes are not exposed to UV radiation from the sun, and oxygen concentrations are lower than in air. Mechanical wave forces are also rarely encountered once DFG is deposited on the seabed. In the Baltic coastal areas, this also applies at shallow densities of a few meters, as only winter storms contain sufficient energy for substantial wave action. Mechanical abrasion might occur if nets are exposed to currents, in which case they will roll over the seafloor and fragment when encountering pebbles or rocks. The shedding of fibres can be very slow with no exposure to mechanical forces, and will be larger in areas with substantial streaming motions. This leads to the introduction of microplastics into the Baltic Sea ecosystem. Given the low salinity and strong salinity gradient, particularly sensitive habitats in the Baltic Sea include blue mussel beds, bladder wreck and eelgrass meadows. Blue mussels are filter-feeding organisms, which were shown to absorb microplastic fibres and particles, leading to

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[1] MARELITT Baltic is co-financed by the EU INTERREG Baltic Sea Programme.

tissue inflammation (von Moos et al. 2012). Regularly caught fish species in the English Channel were also shown to have on average 1-2 microplastic fibres in their stomachs or intestinal tracts, suggesting that unselective feeding behaviour will lead to the uptake of plastic fibres < 5mm in the marine environment. While these studies have not yet proven fibre uptake in the Baltic Sea, it is a question of time until the impacts observed in the North Sea are confirmed for Baltic species.

With the aim to mitigate the impact of derelict fishing gear on the seafloor, MARELITT Baltic strives to:

- Retrieve lost derelict fishing gear from the Baltic Sea
- Decrease the loss of DFG during fishing activities by net marking and awareness building
- Improve harbour reception facilities to allow for discarded and accidentally retrieved fishing gear to be deposited at port and minimise incentive for re-discards or losses at sea
- Develop best-practice guidelines for the retrieval of lost fishing gear and provide guidelines for the recycling of retrieved gear in the sense of a ciruclar economy approach.

Recycling of derelict fishing gear is desirable not only from an environmental perspective, but also because the base material for fishing nets is polyamide 6, which is a valuable raw material in the production of functional and outdoor clothing, backpacks, and other everyday items. If a way can be found to introduce the PA6 from lost fishing nets into the production cycle, this high-value material would not cause harm on the marine ecosystem while at the same time becoming part of the circular economy approach now increasingly tested for plastics.

1.2 MARELITT Baltic net processing & recycling goals

Re-use and recycling of DFG, however, is not an easy task. The fibres become fragile when exposed to salt water and are not as durable as their pristine counterparts. Contamination with other wastes, including the environmental toxins lead, persistent organic compounds such as PCB (chlorinated diphenyls), BPA (bisphenol A) and other additives, hamper the recycling process. In addition, fishing gear retrieved from the sea is usually composed of a mix of materials that cannot be entirely disentangled, even with substantial manual sorting work. These and other challenges have to be overcome before the valuable raw materials are extracted and re-designed for the production chain.

Complexity of the problem:

- Dirty material (can contain mud, oil, tar)
- Mixed polymers
- Large amount of contaminants (sediments, organic matter, metals)
- Fine-grained sediments are hard to remove
- Toxic contamination from lead (gillnets especially!)
- Disentangling of large metal items, rocks, etc.
- Pre-sorting required, and this is hard manual labour
- Wear and tear of machines during cutting and cleaning processes (also sediments act as "grinders" on all stages)

Retrieved fishing gear can be partially embedded in the seafloor and it typically contains large amounts of sediments and organic matter (wood, mussels, fish, ...). Sediments cause wear on machines, and cutters become blunt even more quickly than from fibres alone. The nets and ropes need to be disentangled from large metal items prior to the cutting and cleaning process to avoid machine damage. Retrieved fishing nets and ropes are made of mixed polymers, as the swim lines including floats are made from PE/PP while the base material is composed of PA or PET (polyethylene terephthalate). Flags with swimmers/buoys and ropes originally made from mixed polymers, including PET, additionally complicate the extraction process of the raw materials.

Because of its high polymer and calorific content, DFG can be used as feed material for incineration plants with calorific energy recovery. However, especially in the case of the gillnets the high lead contamination from sink lines requires DFG to be classified as hazardous waste which would lead to dumping in hazardous waste landfills. At the same time, lead itself is a high-value recycling product in the circular economy of metals, such that a retrieval approach for both the plastic and the lead components of DFG is desirable.

Fig. 1.1: Derelict fishing gear retrieved from the Baltic Sea. Lost fishing nets are frequently entangled with a large number of other waste items. Left: Gillnets with styrofoam floats and poles. Middle: Trawl nets containing a fire hose. Right: Shell of an oxygen tank and end piece of a fire hose mixed with nets and other marine litter.

There are only few attempts worldwide to recycle used and discarded fishing nets at the end of their regular lifecycle. These are not lost nets retrieved from the sea and hence are not as contaminated with other waste materials. In the case of gillnets, fishermen remove swim and sink lines and hence the mixed polymer materials and toxic lead weights from the nets prior to disposal. For trawl nets, all parts of the support structure are removed and re-used with new net material when aged net sections become fragile and have to be replaced. In both cases, the discarded material is free from additional impurities and sediments. In particular in the case of gillnets, the base material used since several decades is predominantly PA6, one of the polymer types most easily used in recycling, especially because net material is relatively pristine containing no additives. Discarded net PA6, PP and PE is cleaned and molten into pellets or granules for re-use. In the case of gillnets, the Chilean company Bureo produces skateboards, sunglasses and other beach items from regranulated and pressed fishing nets. The Italian-Slowenian company Aquafil produces yarn from PA6, using only the cleanest and most pristine material to allow for clothing production. The Danish company Plastix recycles trawl nets mainly, either by re-using parts of trawls or traps not yet affected by fragmentation, or by recycling PE and PP into granules then sold to the plastics industry for re-use in the production cycle. All of these efforts mitigate the DFG impact because they imprint an economic value to net material and avoid losses by deposits on the harbour quayside and in the ocean. At the same time, none of the existing systems is capable to treat lost fishing gear retrieved from the sea in the extensive way required for regranulation and recycling into new products. This, however, is required for a true circular economy approach in the fishing sector.

Within the MARELITT Baltic project, one of the goals is to develop a recycling pathway of lost fishing gear. Here, DFG is retrieved from the marine environment, manually pre-processed to allow for shredding, cleaning and regranulation as far as possible with all materials involved. To this aim, WWF Germany as the lead partner in this MARELITT Baltic activity, cooperates with recycling companies and analytics laboratories to test how the material needs to be processed from the moment of retrieval to the potential re-introduction into the production cycle.

In this report, the preliminary results of the processing tests conducted by the WWF Baltic Sea Office in cooperation with partner recycling companies are presented. Achievements, solutions and limitations of recycling options for DFG processing are discussed with the aim to show how a recycling pathway for discarded and lost fishing nets could be implemented in a circular economy approach of the fishing and fishing net industries.

1.3 Tasks to be solved

Pre-sorting: The first step that needs to be addressed is how much pre-sorting and manual processing is needed to allow for further automated processing.

As the shredding stage cannot be done manually, the material has to be prepared to avoid damage on cutting knives, counter-edges and the rotators or other transport mechanisms inside the shredder. The first task therefore was to try different levels of manual extraction of metals and other potentially destructive items, as well as pre-sorting into different fractions such as ropes, nets, and other wastes.

Shredding: Fishing net fibres are sturdy as they are made to last under high weight pressure during work and retrieval in regular fishing operations. They are also made to last in extreme weather and marine saltwater conditions, implying fibres are stable against breakage and cutting. With normal knives in cutters, this implies that blades become blunt quickly and will have to be frequently replaced. This can render net recycling non-economic unless specially designed machines for fibre shredding are employed.

Fig. 1.2: Retrieved lost fishing gear is comprised of a mix of ropes, nets, lines and other materials. Large metal items such as anchors need to be removed to protect machines from damage.

Cleaning of materials: Sediments and other organic matter need to be removed to prepare polymer fibres for regranulation. Before cutting, retrieved fishing nets are heavily entangled and cannot easily be cleaned, as material will be left in crevices and knots. After shredding, fibres have to be cleaned while avoiding wear on cleaning machines. A cleaning method has to be found that processes fine and coarse fibres including both monofilaments as well as conglomerates from shredded woven ropes and netting with an appearance and stickiness of "cotton-wool compounds".

Density separation: High-density polyamides PA and high-density thermoplastics PET need to be separated from polyolefins PE and PP prior to regranulation, as the recycling of mixed materials leads to variable material properties that are difficult to evaluate and re-introduce into the melting and moulding processes. A common type of density separation is a swim-sink bath in saline solution to remove high-density sediment residuals followed by a swim-sink bath in fresh water where PA and PET will sink while polyolefins will float on the surface.

This extraction method needs to be optimised for fishing gear polymers and fibres mixed with other contaminants and organic matter.

These challenges reveal the complexity of the task at hand. Problems such as entanglement of retrieved materials complicating the removal of metal items and other contaminants in the pre-sorting stage, but also entangling of lead and float fragments in fibre balls after shredding need to be solved. When the polymer mix is unknown, the swim-sink bath needs to be adjusted to the floating and sinking fractions, and the properties of the surface and bottom fractions are not well defined. Especially in retrieved and shredded fishing gear, the polymer mix is often unclear.

Currently, there is no “best-practice approach” to the treatment of even end-of-life fishing nets. This is even more true for lost and retrieved fishing gear, as attempts to recycle retrieved material are laborious, time-consuming and need a substantial financial effort before solutions will be found.

The MARELITT Baltic project therefore sets out to develop a new approach and recommendations of how lost fishing gear can be re-introduced into the recycling process, avoiding the valuable and high-energy materials to enter landfills, thereby causing a secondary impact as plastic waste into the terrestrial environment. The first step on this way towards the reuse of lost fishing gear is to demonstrate the feasibility of net recycling and what is technically feasible given the material challenges, and to reveal what might be inefficient. The result of these practical tests and chemical-physical material properties evaluation will be guidelines and recommendations for the recycling of fishing gear lost and retrieved at Sea.

2. Mechanical processing of DFG

2.1 Introduction

The first stage of waste material processing typically involves sorting and shredding. Preparation for recycling additionally implies a thorough cleaning stage before re-granulation becomes an option. The processing stages were tested at Vecoplan AG.

Vecoplan AG is a German engineering company that designs and manufactures machines for the waste sector. Their offering includes machines for shredding and washing that are used to pre-treat plastic materials prior to recycling. In their main plant in Bad Marienberg the company operates a Technology Centre which gives industrial and other external partners the opportunity to test Vecoplan’s machines for new applications.

Within the context of the MARELITT Baltic project, this facility was used to investigate the technical feasibility of a pre-treatment process to enable DFG recycling. This involved sorting, shredding, density separation, washing and grinding (Fig. 2.1).

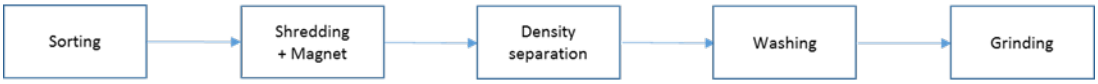


Fig. 2.1: Schematic overview of the pre-treatment processes conducted at Vecoplan

The aim of sorting was to better understand the material composition of DFG and to remove large metal pieces that would otherwise damage the shredding machine. The shredding was necessary to obtain smaller homogenous pieces of DFG to facilitate handling and enable the density separation and washing process. The density separation had the aim to separate high density materials such as metals, sediments and mussels from the less dense polymer fibres. The polymer fibres were then washed to further remove impurities such as embedded sediments. Some of the washed material was grinded to increase its pourability in preparation of an injection moulding trial outside the premises of Vecoplan.

All processes took place between 17 to 19 March, 3 May and 22 to 23 June 2017. They were conducted by U. Kramer, A. Grose and S. Kolodzey from Vecoplan, F. Schneider from the University of Bath, Dr. A Stolte from WWF Germany and Dr. M. Krüger from Karl Tönsmeier Entsorgungswirtschaft GmbH, a German recycling company and associated partner in MARELITT Baltic.

2.2 Materials and methods

2.2.1 Materials

As input material 2095 kg of DFG were sent to Vecoplan at the beginning of March 2017. The material was mainly composed of trawl nets, gillnets and ropes. The content and mix of each big bag depended on the location of the retrieval activity.

DFG from Sassnitz
Vecoplan received 727 kg of DFG from Sassnitz dominated by trawl nets (Fig. 2.2). However, anchors, cables, metal chains, fire hoses and mussels were also part of this material mix.

DFG from Ahlbeck
DFG from Ahlbeck mainly contained gillnets (Fig. 2.2). Lead lines, PE/PP swim lines, wood and mussels were also contained in the material. A total of 868 kg of this material was sent to Vecoplan.

DFG from wreck cleaning

The DFG from a wreck cleaning campaign in 2014/2015 was manually sorted and mechanically dry-cleaned at the recycling company Metallex in Bytom Odrzański in Poland, so that contaminants including metals, buoys/swimmers and organic material were no longer present in the material. The 500 kg that were sent to Vecoplan consisted of two fractions: ropes and trawl nets (Fig. 2).

Predominantly trawls- nets

Contaminating materials: Anchors, cables, metal chains, fire hoses, etc.

Predominantly gillnets

Contaminating materials: Lead lines, PE/PP swim lines, wood, mussels, fish fragments, etc.

Ropes and trawl nets

No Contaminants
Metal, buoys/swimmers, organic material removed

Fig. 2.2: Input material from Sassnitz (left), Ahlbeck (middle) and wreck cleaning (right), © F. Schneider

2.2.2 Methods

Processing pathways

Sorting is the first pre-treatment process of DFG recycling. It is required to remove contaminants for a subsequent shredding process. Sorting was conducted with different levels of manual effort. DFG from the wreck cleaning was fine-sorted at a net sorting facility in Poland, whereas DFG from Sassnitz and Ahlbeck was either fine- or rough-sorted at Vecoplan in Germany. The most labour intensive sorting approach is "fine-sorting" because it involves a manual separation of all waste fractions. "Rough-sorting" focuses on the removal of large metal items and is thus considered the least labour intensive sorting approach.

Each sorting approach changes the requirements for the following pre-treatment processes. Rough-sorted material requires both rough- and a fine-shredding in order to cope with potentially undetected metal pieces. Fine-sorted material can directly be fine-shredded because of the higher sorting quality. After shredding, a density separation is necessary for both rough- and fine-sorted material to remove sediments, lead, mussels and other impurities. After density separation, a washing process can further reduce impurities. Grinding is an optional process step to improve the pourability if an extrusion of the material is intended.

Table 2.1 gives an overview of the pre-treatment processes employed. Due to time constraints the density separation and washing could only be completed for part of the rough-sorted material and due to technical challenges most fine-sorted ropes could not be washed.

Table 2.1: Processing pathways. All processing pathways conducted on each type of input material are denoted with "X", "P" indicates that the process could only be partially completed. See Table 2.3 for a complete overview of available material flows.

Sorting Approach	Material Origin	Material Fraction	Shredding		Density separation		Washing	Grinding
			Rough-	Fine-	Stage 1	Stage 2		
Pre-Sorting	Wrecks	Nets		X			X	
		Ropes		X			P	
Fine-Sorting	Sassnitz	Ropes		X	X		X	X
		Clean nets		X	X		X	
		Dirty nets		X	X		X	
	Ahlbeck	Nets & ropes		X	X	X	X	
Rough-Sorting	Sassnitz	-	X	X	P	P		
	Ahlbeck	-	X	X	P	P	P	

Sorting

At Vecoplan's Technology Center sorting was done manually in two setups: a very detailed fine-sorting and a less detailed rough-sorting. Prior to sorting setups every big bag was brought inside the facility and their initial weight was taken. The pre-sorted nets and ropes from wrecks were also weighed at this point.

Fine-Sorting

During fine-sorting nets and ropes were cut free from other materials using knifes, cutters, pincers and similar tools. A crane facilitated this task as it allowed lifting the material into a more accessible upright position (Fig. 2.3). The extracted materials were separated into seven material groups: ropes and nets, metal, wood, stones, textiles, mussels and other. In the case that the input material was covered in mud, a pre-cleaning step was conducted. For this the material was mounted on a crane and lowered into a water bath where it was stirred manually so that the mud could dissolve in the water. At the end of the fine-sorting each material group was weighed. The nets and ropes were then fine-shredded whereas the other materials were treated as general waste.

Input material from Ahlbeck

Input material from Sassnitz

Input material from Sassnitz

Input material from Sassnitz

Fig. 2.3: Fine-sorting of DFG, © F. Schneider

Rough-Sorting

During rough-sorting visible metal pieces, typically larger than ten centimetres, were removed as they would have negatively affected the subsequent shredding process. For instance, during one rough-shredding test, the counter triangles of the shredding machine were ejected from their mounts because of the presence of larger metal items and small rocks. The DFG was mounted on a crane and mechanical tools were used to cut out metal chains and anchors carefully to avoid entanglement in the net material (Fig. 2.4). After rough-sorting the larger metal pieces were weighed and then given to a scrap recycler whereas the remaining material was directly lifted into the rough-shredding unit.

Input material from Ahlbeck inside an excavator shovel

Input material from Sassnitz mounted on a crane

Removal of large metal items with mechanical cutting tools

Cutting tool entangled in net

Fig. 2.4: Rough-sorting of DFG, © F. Schneider

Shredding

Two shredding machines with different configurations were used for rough- and fine-shredding (Fig. 2.5). The power of the shredder as well as the size of the sieve diameter and U-rotor indicate the type of materials that can be shredded with the shredding machines. For rough-shredding a more powerful shredder with larger sieve diameters and knifes on the U-Rotor had to be chosen as compared to the fine-shredding unit (Fig. 2.5).

120mm diameter sieve and U-rotor of VAZ 2000 MNFT used for rough-shredding

U-rotor of VAZ 2000 MNFT for rough-shredding

VAZ 1600 M XL T with 20-30mm diameter sieve and a U-rotor for fine-shredding

U-rotor of VAZ 1600 M XL T for fine-shredding

Fig. 2.5: Configuration of the rough- and fine-shredding machine, © F. Schneider

Rough-Shredding

For the rough-shredding trial the uniaxial VAZ 2000 MNFT was equipped with a 120mm diameter sieve and a U-rotor holding 48 cutting crowns of 80mm x 80mm (Fig. 2.5). For the process itself, the material was inserted through the top lid, shredded by a cutter wheel rotating against a set of counter knives and the resulting fragments were transported to a magnet which separated metal pieces from the remaining material (Fig. 2.6). The rotor has a back-turning mode which is activated as soon as the resistance on the rotor reaches a certain threshold which avoids the machine to get stuck. The back-turning is a special and crucial characteristic of the Vecoplan shredders and it allows difficult materials such as nets to be efficiently cut without blocking the machine. After rough-shredding the weight of the shredded materials was taken.


Material input

Shredding process

Conveyor belt and magnetic metal extractor

Fig. 2.6: Process of the rough- and fine-shredding with subsequent magnetic separation, © *F. Schneider*

Fine-Shredding

The fine-shredding trial was conducted on Vecoplan's uniaxial VAZ 1600 M XL T. It was mounted with a U-rotor containing 72 cutting crowns of 40mm x 40mm dimension (Fig. 2.5). For the rough-sorted materials a sieve diameter of 30mm was used whereas a sieve diameter of 20mm was used for the pre-sorted and fine-sorted materials. Although the fine-shredding was conducted on a less powerful shredding machine, the process works in the same way as rough-shredding (Fig. 2.6). In the following, all fractions called "fine-shredded" refer to the output of this shredding stage using a 20-30mm diameter extraction sieve.

Density separation

The density separation was carried out in two stages. During the first stage saline water was used as solution whereas normal tap water was used for density separation during the second stage (Fig. 2.7).

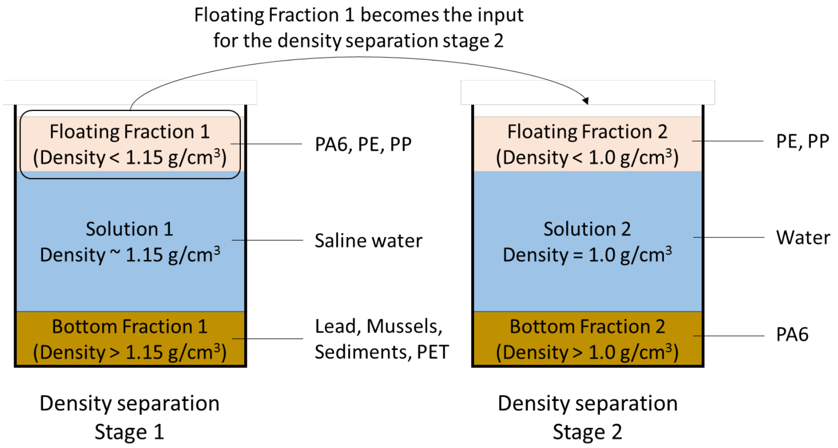


Fig. 2.7: Schematic overview of the density separation

First stage

For the first stage of the density separation a 1000 litre tank was filled with tap water and anti-icing street salt (Fig. 2.8). The solution was stirred until the salt was resolved. It was ensured that the amount of salt applied led to a residual salt fraction at the bottom of the tank, such that the saline solution could not be saturated further. It has to be noted that this salt is impure and will therefore not lead to a fully saturated NaCl solution. While a saturated NaCl solution would have a density of 1.2 g/cm^3, we expect the achieved solution density to be around 1.15 g/cm^3. This was tested by a hard-moulded PA6 sample to ensure that PA6 would indeed float during the first stage of the density separation.

Anti-icing street salt as input material

Tank filled with saline water

Tank filled with tap water

Fig. 2.8: Setup of the density separation, © F. Schneider

After preparing the tank, batches of the fine-shredded material were introduced into the saturated saline water and stirred (Fig. 2.9). It was expected that high density materials such as lead, mussels and sediments sink and the anticipated less dense polymer fractions float (Table 2.2). The floating fraction was manually extracted with standard household sieves and squeezed to reduce its humidity (Fig. 2.9). Ultimately, the solution was released from the tank revealing the bottom fraction. In the following, the outputs of the first stage of the density separation will be called "floating fraction 1", "bottom fraction 1" and "solution 1". The floating fraction 1 was given to the second stage of the density separation whereas the bottom fraction 1 and solution 1 were treated as hazardous waste due to their potential lead contamination.

Table 2.2: Densities of expected materials in the fine-shredded output fraction (source: Wikipedia)

Material	Lead	Mussels Calciumcarbonate	Sediments Silicates	PET	PA6	PE	PP
Average Density (g/cm^3)	11.34	2.73	2.5	1.37-1.68	1.08-1.23	0.93-0.97	0.90-0.92

For all materials the used amount of water and salt was recorded. Separate tanks were prepared for the materials “Sassnitz ropes” and “Ahlbeck nets and ropes”. In order to save time and resources, the materials “Sassnitz clean nets” and “Sassnitz dirty nets” were processed after each other in the same saline water. Similarly, the materials “Sassnitz rough” and “Ahlbeck rough” shared the same process water. Although a sequential processing allowed obtaining separate floating fractions 1, it also created a joint bottom fraction 1 and solution 1. The weight of the bottom fraction was measured for “Sassnitz ropes” and “Ahlbeck nets and ropes”.

Second stage

In preparation of the second stage of the density separation a tank was filled with tap water. Then, the floating fraction 1 was placed into the water and stirred. In the water tank the denser polymer fibres such as PA6 were expected to sink whereas other polymer fibres such as the polyolefins PE and PP were expected to float (Table 2.2). The upcoming floating fraction, presumably polyolefins with densities lower than water, was extracted with household sieves and stored in a separate container. Finally, the solution was released from the tank to obtain the bottom fraction. The bottom fraction was squeezed and stored in a hanging big bag overnight to reduce its humidity. In the following, the outputs of the second stage of the density separation will be referred to as “floating fraction 2”, “bottom fraction 2” and “solution 2”. Although there was not enough material of “floating fraction 2” for a washing process there is a potential to clean and recycle this material as well. Bottom fraction 2 was passed on to the washing process and solution 2 was released to the public sewage system.

Input of the fine-shredded material

Stirring the input material in the solution

Extraction and squeezing of the floating fraction

Release of the solution to retrieve the bottom fraction

Fig. 2.9: Density separation process, © F. Schneider

The materials “Sassnitz ropes”, “Sassnitz clean nets” and “Sassnitz dirty nets” were not subject to the second stage of the density separation but instead they were directly stored in big bags. For the remaining materials, the amount of input water and floating fraction 2 was weighed.

Process improvement trial

The use of standard household sieves made the density separation very labour-intensive. To improve this, a box sieve was also tested (Fig. 2.10). At the beginning, the box sieve was immersed in the solution. Then, the fine-shredded fibres were given to the solution within the area of the box sieve and stirred. After a few minutes the middle layer of the sieve was inserted before lifting the box sieve (Fig. 2.10). Finally, the box sieve was opened so that the floating fraction and middle layer could be removed. However, the initial fibres were not large enough to be captured using this coarser sieve. The losses were so high that the shredding process was adjusted to obtain larger fibres. Even with larger fibres the process was not faster compared to household sieves because the handling of the box sieve required much more time.

Fig. 2.10: Density separation trial with larger and coarser sieve, © F. Schneider

Washing

The friction washer Vecoplan HydroDyn and its washing programme "Foil" were used for the washing process. This typically allows 600 kg/h of solid material to be washed using 15m^3 of process water. First, the input material was inserted (Fig. 2.11) which was then transported via a dosing and plug screw to a plastic cleaning unit where input water pressed the material through grooves and notches on the surface of two counter-rotating discs (Fig. 2.11). In these friction discs, angular momentum transports the material outwards, removing residual sediment and other fragments from polymer fibres ("friction cleaning"). Through a pump the slurry was transported to a water separation unit removing solid material larger than 2.5 mm from the remaining water. The solid material was collected in a big bag whereas the remaining water was sent through a curved sieve (Fig. 2.11) in which solid material larger than 0.5 mm was removed. Ultimately, the process water was cleaned in a two-stage floatation process and returned as input water to the machine.

Material input
© A. Stolte

Friction discs
©U. Kramer

Curve sieve output
© A. Stolte

Material input (left) and output (right)
© A. Stolte

Fig. 2.11: Friction washer – overview of the Vecoplan washing unit

Grinding

The grinding was conducted on Vecoplan's VD 1100 machine. It was equipped with five rotating and two stationary rows of blades as well as a 6mm diameter sieve. Before the grinding started the input material was introduced into the feed hopper (Fig. 2.12). During the grinding process gravity leads the material to the blades which cut it into smaller fibres. Once the fibres were small enough they fell through the sieve so that the output could be collected (Fig. 2.12).

Fine-grinding mill input
© F. Schneider

Fine-grinding mill output
© F. Schneider

Fig. 2.12: In- and output of the fine-grinding mill

2.3 Results

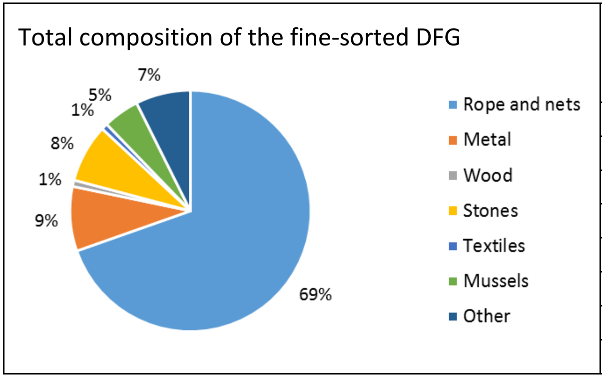
2.3.1 Fine-Sorting

Process

Fine-sorting was very labour-intensive. It took approximately 20 person hours to fine-sort three big bags from Sassnitz weighing 450 kg in total and approximately three person hours for one big bag from Ahlbeck weighing 85 kg. The material from one big bag from Sassnitz required pre-cleaning because it was excessively covered in mud. The cutting tools turned blunt quickly which is why fine-sorting was not an acceptable solution for the entire two tonnes of DFG material. Therefore, a rougher initial sorting process was proposed for the major amount of the retrieved DFG.

Output

Rope and net material were the main fraction of the fine-sorted DFG from Ahlbeck and Sassnitz accounting for 330 kg (Fig. 2.13). The material groups: metal, stones, other, mussels, wood and textiles, made up 9%, 8%, 7%, 5%, 1% and 1% of the total weight in this order, respectively (Fig. 2.13). The category other waste contained various items including cables, sea-water filled bottles, and plastic packaging. It must be noted, however, that the lead lines were too entangled in the gillnet material from Ahlbeck such that lead could not be removed. Lead is expected to be the dominant weight fraction in the extracted "ropes and nets" from Ahlbeck.



Material groups	Sassnitz	Ahlbeck	Total
Rope and nets	264 kg	66 kg	330 kg
Metal	41 kg	-	41 kg
Wood	4 kg	-	4 kg
Stones	37 kg	-	37 kg
Textiles	4 kg	-	4 kg
Mussels	21 kg	2 kg	23 kg
Other waste	20 kg	15 kg	35 kg
Total	391 kg	83 kg	474 kg

Fig. 2.13: Material composition of fine-sorted DFG from Ahlbeck and Sassnitz

Sassnitz

The total weight of the fine-sorted material from Sassnitz was 391 kg (Fig. 2.13). Rope and nets accounted for 264 kg which were further divided into ropes, clean and dirty net fragments (Fig. 2.14). The distinction between clean and dirty nets was made because a quality difference between the two extracted material types was visually identified. In particular, the nets classified as "dirty" contained various types of net materials including gillnets. Metal, stones, mussels and other waste accounted for 41 kg, 37 kg, 21 kg and 20 kg in this respective order whereas wood and textiles accounted for 4 kg each. The material loss during fine-sorting was 59 kg which may be explained by sediments (Fig. 2.15) that were extracted during the pre-cleaning to protect the shredding machine. Also the weight of the three big bags, mussels and sediment which fell on the floor and the evaporation of water may add to the loss.

Sassnitz ropes

Sassnitz Clean Nets

Sassnitz Dirty Nets

Ahlbeck nets and ropes

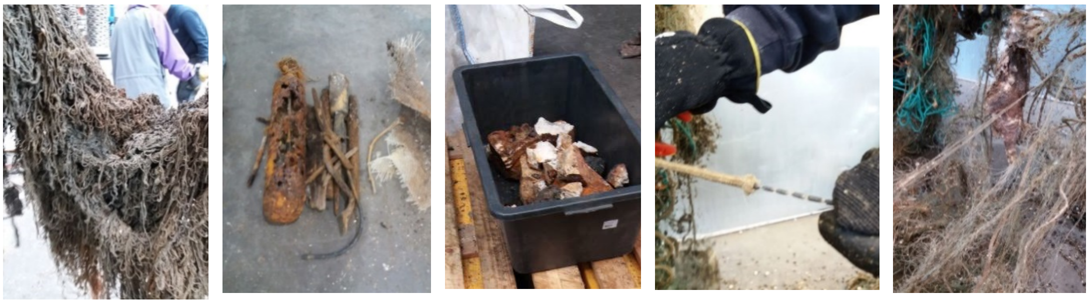
Fig. 2.14: Remaining material after fine-sorting, © F. Schneider

Some of the noticeable items which were categorised as other waste were fire hoses, cables, shoes, and even a textile balloon was found. Apart from large stones, anchors and metal chains also one corroded oxygen tank (Fig. 2.15) was removed which would have hampered the shredding process.

Ahlbeck

Fine-sorting of the gillnets from Ahlbeck resulted in a total of 83 kg of output material divided into three fractions. Ropes and nets accounted for 66 kg, other waste for 15 kg and mussels for 2 kg of the output weight (Fig. 2.13). For the ropes and nets fraction, no further material separation was possible because the DFG was too heavily entangled. This implies that sink lines composed of lead pieces embedded in polymer lining were left in the gillnet samples. It has to be expected that the lead dominates the weight of the Ahlbeck sorted output due to its density of 11.34 g/cm3 as compared to PA6 with 1.15 g/cm3. The final weight of the sorted output can therefore not be compared with the polymer contribution as in the case of the Sassnitz sample dominated by trawl nets and ropes. There was a 2 kg material loss during fine-sorting of the Ahlbeck sample which can be explained by the mussels and sediments that have fallen to the floor and the weight of the big bag itself.

The category "other waste" did comprise not only various plastic products such as three bottles filled with sea water, but also dead fish and lead lines (Fig. 2.15). The toxic lead and the dead fish which emitted an unpleasant smell stood out as potentially harmful and challenging materials for further recycling.



Net covered in mud/sediments

Corroded oxygen tank and other metal pieces

Stones

Sinkline composed of lead fragments in polymer lining

Dead fish in a gillnet

Fig. 2.15: Potentially hazardous items for humans and/or machines

2.3.2 Rough-Sorting

Process

The rough-sorting was much faster than the fine-sorting. It only needed 0.5 person hours to remove larger metal pieces from one Sassnitz big bag weighing 277 kg and approximately 3 person hours for eight big bags from Ahlbeck with a total weight of 783 kg. However, when comparing to fine-sorting, rough-sorting also increased impurities of the desired net and rope material because mussels, wood and other items were not removed. This means that the subsequent processing steps need to cope with a higher degree of contamination than in the case of fine-sorted material. Also, not all larger metal pieces were successfully removed as the rough-shredding showed. One explanation for this is that not all metal pieces were visible or too entangled in net material to be removed during rough manual sorting. While time and manual person effort are much more efficient in the case of rough-sorting, two disadvantages were identified. The washing quality might be compromised because of the higher content of residual sediments, grains, and other contaminating fragments. In addition, fine-sorting enabled the separation of ropes and different types of nets, which led to a cleaner polymer fraction for recycling trials. Rough-sorting does not provide the option to separate individual materials, such that the potentially following recycling options might be reduced.

Output

The output materials from rough-shredding are displayed in Fig. 2.16.

Removed metal from Sassnitz sample

Sassnitz sample after rough-sorting

Removed metal from Ahlbeck sample

Ahlbeck sample after rough-sorting

Fig. 2.16: Material outputs from rough-sorting, © F. Schneider

Sassnitz

During rough-sorting 4 kg of metal (Fig. 2.16) were extracted from one big bag of the Sassnitz sample weighing 277 kg. This amounts to 1.4% of the input weight which is considerably less than the 9% of metal which were removed from the same type of material during fine-sorting. This indicates that fine-sorting is much more precise than rough-sorting. It is not possible to determine the material loss during this process, because the weight of the roughly sorted output fraction was not measured. However, it is reasonable to assume that some material loss -- for example mussels and sediment dropped to the floor -- during material handling or in the form of water evaporation will have occurred.

Ahlbeck

From the eight big bags containing DFG from Ahlbeck, 53 kg of larger metal pieces (Fig. 2.16) could be extracted which amounts to 7% of the 783kg of input material. The metal pieces were mainly comprised of anchors and chains. Such large and heavy metal pieces were not present in the Ahlbeck sample used earlier in the fine-sorting process. Attached to the metal was a small fraction of rope and net material which would have been too time-consuming to regain.

The amount of other material loss such as mussels was not possible to determine because the weight of the rough-sorted output fraction was not measured.

2.3.3 Rough-Shredding

Process

The processing of the Sassnitz input material took 10 minutes during which the average power output of the engine was 44.4 kW. The material from Ahlbeck needed 18 minutes causing an average power output of the engine of 50 kW. Large metal pieces such as notches and possibly other hard materials frequently activated the back-turning mode of the shredding machine which prevented a smooth operation. The input material caused notable wear on the cutting crowns and counter knifes and it was therefore estimated that they would only last 40 to 80 machine hours before a replacement would be required with roughly sorted DFG input material. This wear of machine parts and energy consumption need to be considered when DFG recycling should be economically viable.

Output

The combined metal output of the magnetic separator was 16 kg from Ahlbeck and Sassnitz input materials (Fig. 2.17). This amounts to 2% of the total rough-shredding output. However, it is not possible to derive how much metal was present in each input material individually because the metal was not captured separately.

Fig. 2.17: Metal fragments collected by the magnetic separator after rough-shredding, © F. Schneider

Sassnitz

The rough-shredding trial resulted in 243 kg of coarse fibres, netting and rope pieces from the Sassnitz input material (Fig. 2.18). The characteristic fibre length was approximately 100 to 120mm. Sassnitz material was shredded first and it can be expected that some material was left inside the shredding machine which increased the Ahlbeck output. It is not possible to determine the material loss during rough-shredding because the amount of each input material was not measured (cf. Table 2.3).

Ahlbeck
The input material from Ahlbeck resulted in 706 kg of rough-shredded fibres and larger conglomerates. Although the material composition was not immediately analysed, it is apparent that the material consists of a wide material mix (Fig. 2.18) including lead and possibly other harmful substances.

In order to remove the lead from the Ahlbeck sample as early as possible, a first density separation step was attempted directly after rough-shredding. However, density separation at this stage was not feasible because the rough-shredded material was too intertwined such that the lower density fraction could not be separated from the higher density conglomerated material. In particular, lead fragments in polymer lining originating from sinklines could not be extracted and caused a large amount of the gillnet material to be dragged to the bottom and lost for further processing. An additional manual density separation stage was therefore not considered productive to optimise polymer fibre output immediately after rough-shredding.

Fig. 2.18: Rough-shredded material from Sassnitz (left) and Ahlbeck (right), © F. Schneider

2.3.4 Fine-Shredding

Process
Fine-shredding worked without any problems for all input materials. The time and power output of the engine was not measured for the fine-sorted materials from Sassnitz. The fine-sorted Ahlbeck material needed 33 minutes (min) and generated on average 16 kW of machine power. The fine-shredding of the pre-sorted nets from wrecks took 45 min and lead to 44 kW power output of the engine. The pre-sorted ropes from wrecks were shredded within 50 min and caused an average engine power output of 102 kW. Rough-sorted material from Sassnitz took 20 min and rough-sorted material from Ahlbeck needed 30 min for fine-shredding. Both materials required on average 60 kW of energy consumption.

Output
Some fishing hooks as used in recreational fishing were present in most samples and extracted by the magnetic separator immediately after shredding.

Pre- and fine-sorted materials

The pre-sorted DFG retrieved from wrecks, 440 kg of ropes and 60 kg of nets, as well as the ropes and nets of the fine-sorting trial were shredded using a 20mm diameter sieve which led to fibre lengths of approximately 20mm to 40mm (Fig. 2.19). The amount of retrieved material was not determined so that the material loss during this process step cannot be evaluated. As expected, there was no notable metal output because metal pieces had been removed during pre-processing.

Rough-sorted materials

The rough-sorted Ahlbeck and Sassnitz samples were shredded with a 30mm sieve which gave approximately 30mm to 50mm long fibres (Fig. 2.19). The material from Sassnitz resulted in 219 kg of fine-shredded fibres and the material from Ahlbeck in 678 kg. There was no notable metal output at the magnetic separator for both material inputs. As lead is non-magnetic, it could not be extracted by the magnetic separator and remained in the fine-shredded fibre mix. The input material from Sassnitz was shredded before the Ahlbeck material so that some of the remaining Sassnitz material will have added to the total Ahlbeck output. This might explain why approximately 40 kg of the Sassnitz and only 28 kg of the Ahlbeck material were lost during the fine-shredding process.

Pre-sorted materials		Rough-sorted materials	
			
Pre-sorted ropes retrieved from wrecks	Pre-sorted nets retrieved from wrecks	Ahlbeck rough-sorted	Sassnitz rough-sorted
Fine-sorted materials			
			
Sassnitz fine-sorted ropes	Sassnitz fine-sorted clean nets	Sassnitz fine-sorted dirty nets	Ahlbeck fine-sorted nets & ropes

Fig. 2.19: Fine-shredded material outputs, © F. Schneider

2.3.5 Density separation

Process

The manual density separation was very labour-intensive. The extraction of the two floating fractions took approximately 8 person hours for 100 kg of Ahlbeck material and approximately 10 person hours for 100 kg of Sassnitz material. The difference can be explained by the higher lead content of gillnets retrieved in Ahlbeck which reduced the time-consuming manual extraction of the floating fraction as compared to the Sassnitz sample of trawl netting and ropes, but also led to larger fibre losses in the sinking fibre-lead fragment mix during the first density separation stage.

Immediately after inserting, most of the input material sank to the bottom of the saline water tank. Stirring the solution helped to increase the floating fraction over time. It was difficult to measure the weight of the bottom fraction and water loss because the deep tanks did not allow easy extraction of the sunken fraction.

Output

Fine-sorted materials

Sassnitz ropes were processed in a mixture of 400 litre of water and 125 kg of de-icing salt. After density separation, approximately 100 litres of the solution were removed from the saline water tank. The extracted bottom fraction of the saline water tank weighed 22 kg. It did not only reveal a large amount of sediment but also polymer fibres which should have floated in the tank. It is likely that sand or other contamination adhering to the material caused the polymer fibres to sink.

The density separation of Sassnitz clean nets and Sassnitz dirty nets took place in a mixture of 700 litres of water and 175 kg of de-icing salt. The amount of water loss and the weight of the bottom fraction was not recorded.

The first stage of the density separation of Ahlbeck fine-sorted gillnets in 700 litres of water and 175 kg of salt resulted in a bottom fraction of 12 kg that mainly contained sediment, lead and polymer fibres attached to lead fragments and sediments which impeded floating. The second stage of the density separation in pure water resulted in a floating fraction of 4 kg which was grinded and given to an external laboratory for analysis. This fraction contained fragments from floats embedded in the swim lines of the gillnets which are characteristically made of PE and PP polyolefins. The bottom fraction which was expected to be composed predominantly of polyamide fibres from the gillnets and residual sediments not removed during density separation stage 1 was not sufficient to generate a usable output after the washing process and was therefore not used further.

Rough-sorted materials

First, 16 kg of the Sassnitz sample and then 292 kg of the Ahlbeck sample were processed. The remaining 203 kg of Sassnitz and 386 kg of Ahlbeck material could not be finished in the time available during the three extensive testruns at Vecoplan's technology centre. The remaining Ahlbeck gillnet sample was used for hydrolysis and pyrolysis trials as described in Section 5.

The bottom substrate of the saline water tank revealed a large amount of lead in addition to sediment and polymer fibres. The weight of this fraction and the water loss were not determined.

However, a water sample was taken for external chemical analysis to probe lead contamination in the waste water of the density separation stage.

The floating fraction in the pure water tank derived from the roughly sorted Ahlbeck gillnet sample weighed 18 kg. It mainly consisted of brown and white plastic fragments although mono-fibres were also present (Fig. 2.20). The bottom fraction of the Ahlbeck gillnet sample was passed on to the friction washer for further processing and was used for material recycling experiments at the University of Magdeburg-Stendal as described in Sec. 6.

The floating fraction 2 from the mixed netting and ropes from Sassnitz were not further analysed. The bottom fraction 2 of the Sassnitz mixed, roughly sorted sample was not sufficient to generate a notable output after the following friction washing trial and was hence not used further.

Fig. 2.20: Floating fraction of the Ahlbeck sample extracted from the pure water tank, © F. Schneider

2.3.6 Washing

Process

The time and energy consumption of the washing process was not measured but it is estimated that the washing requires 100 kWh per tonne. The water loss depends on the water absorbability of the input material and the effectiveness of the water separation unit. It was estimated that for washing one tonne of the input material between one and three m^3 of water would be required. For the washing several chemicals were used. Per one m^3 of water 0.04 litre of PolySepar CFX 1088 - a combination of Di-aluminium chloride pentahydrate and aluminium chloride – were added to enable the flocculation of the residuals. Furthermore between one and three litre of a solution containing 99.8% of water and 0.2% of the polymer PolySepar PK 1455 were added to one m^3 of process water. In order to maintain a pH value between 7.9 and 8.2 a caustic soda solution was automatically added to the process water. It is not possible to extrapolate the amount of chemicals that would be required at an industrial scale because the small amount of input material used for this study may not have been enough to achieve a chemical balance in the solution. It takes several hours and days for the process to get into a balanced state under industrial conditions, and the friction washer was operated for a maximum of several hours for each washing trial.

The washing was possible for all input materials except for larger amounts of fibres from rope material. Here the material got stuck between the cleaning unit containing the friction discs and the water separation unit where waste water is extracted and passed on to the water treatment tanks.

Blockage of the pump sucking the material from the output tank below the friction discs upwards to the water separation unit caused the tank to overflow for all fine-fibre input materials (rope and trawl net fibres). This required the tank to be drenched and the pump filter to be cleaned, reducing time efficiency drastically. The feeding blockage was the reason that most of the input material from the rough-sorted, mixed Sassnitz fraction could not be washed. The gillnet-dominated material from Ahlbeck was not prone to filter blockage due to the thicker and less fluffy fibres. It is worth pointing out that Vecoplan has solved this problem for their customers with a different machine design. This requires the cleaning unit to be directly placed above the water separation unit so that the intermediate tank is eliminated. The ceiling of Vecoplan's Technology Center is not sufficiently high to permit this configuration.

Output

The collected fibres of less than 2.5mm at the curved sieve were not investigated for each input material. However, in general it can be said that the materials from the curved sieve contained a large amount of polymer fibres which were lost during the process.

The washed fibres had a humidity of up to 30% which is too high for further processing e.g. in melting extruders for pellet generation. Usually a drying process is required to reduce the humidity to not more than 12% for subsequent extrusion. In industrial processing strands, a mechanical or thermal conveyor belt follows the cleaning process to dry the material to the required residual humidity levels. A drying unit is not available at the Technology Center such that this stage could not be tested. The washed fibres had an unpleasant smell which can be linked to contamination in the processing water. However, it is unclear if this is affecting the quality of the material output.

Although the output of the washing process (Fig. 2.21) was visually much cleaner than the input material, some sediments remained attached to the material and the washing process itself may have added impurities to the input material. This is because material rests such as foil and organic microorganisms from previous washing tests might have remained in the friction washer. The analysis of the washing quality confirmed the pre-sorted ropes and nets from wrecks to have the highest residual suspended particle contamination. Extracted ropes and nets from Sassnitz during fine-sorting showed a much lower turbidity and gillnet material from Ahlbeck led to an almost clear solution in the washing quality test. Again, it can be concluded that the coarse fibres of the gillnets are most efficiently cleaned in the friction washer, while fluffier fibre materials trap residual sediments or fine-grained organic matter that lead to a pourer washing quality.

Pre-sorted materials

Rough-sorted materials

Pre-sorted ropes from wrecks

Pre-sorted nets from wrecks

Ahlbeck rough

Not enough input material for the friction washer to generate output

Sassnitz rough

Fine-sorted materials

Sassnitz rope

Sassnitz clean nets

Sassnitz dirty nets

Not enough input material for the friction washer to generate output

Ahlbeck nets & ropes

Fig. 2.21: All washed fibres from Ahlbeck, Sassnitz and wrecks, © F. Schneider

Pre-sorted materials

The pre-sorted ropes from wrecks caused a blockage during the washing process such that 312 kg of the ropes could not be washed. The small fraction that was washed resulted in 62 kg of washed rope material. As for the pre-sorted nets from wrecks, 66 kg of washed fibres could be obtained. The increase of weight compared to the 60kg of input material can be explained by humidity absorption of the washed fibres.

Fine-sorted materials

The ropes, clean nets and dirty nets from Sassnitz lead to 33 kg, 37 kg and 111 kg of washed polymer fibres from 62 kg, 52 kg and 150 kg of input material entering the fine-shredding stage, respectively. The fine-sorted material from Ahlbeck was used to clean the friction washer and no output was collected from this step.

Rough-sorted materials

The rough-sorted material from Sassnitz was also used to clean the friction washer because its amount was not enough to get a meaningful output from the washing process. The roughly sorted Ahlbeck material resulted in 54 kg of washed fibres from 292 kg of input material (prior to density separation). Because of the high density and weight of the sediment (2.5 g/cm^3) and lead (11.3 g/cm^3), the gillnet-dominated samples lost a substantial amount of up to 80% of their weight during the density separation and the following washing process.

2.3.7 Grinding

Process

The grinding worked very well for the ropes extracted from the Sassnitz sample during fine-sorting. The energy consumption of this process was not measured. It took approximately 10 minutes to grind about 20 kg of washed rope material.

Output
The output of grinding the fine-sorted rope material from Sassnitz was 20 kg of fibres with fibre lengths in the range 4 to 6mm.

2.4 Limitations and future work

In this section, a brief summary of the immediate results of the processing trials is given. A more detailed analysis of the processing limitations and requirements including possible solutions is provided in Section 3.

Sorting
The study showed that fine-sorting is very labour-intensive and therefore not viable for a large-scale operation. Nevertheless, it achieved a high level of metal and stone extraction which allowed the smooth operation of the shredding machine. It also helped to identify hazardous materials such as dead fish and lead line. Even though, it was not possible to remove large quantities of the entangled lead line. A detailed evaluation of the input material will be useful in any future DFG processing operation to prevent damage from possibly other hazardous materials such as residual fragments of ammunition for example containing phosphorus.

Rough-sorting is a very fast process which is particularly beneficial for a large-scale operation. However, the high level of remaining metal fragments led to complications during the rough-shredding stage and will lead to rapid wear of the cutting edges and counter triangles in a larger-scale operation. Also, other potentially harmful materials to humans or the machine were not detected and removed. Although this does not seem to have influenced the recycling process of this study, it may be a risk for other recycling trials.

In the future, fishermen can be asked to carry out a first evaluation of the retrieved DFG in the harbour where they are landed. Fishermen usually know the types of plastics involved in each type of netting, and they can visually evaluate the level of contamination, e.g. the entanglement with lead lines or other metal pieces difficult to remove, overgrowth with organic matter, etc. The retrieval operation itself may be conducted in such a way that excessive amounts of sediments are removed which avoids an additional pre-cleaning process, e.g. by dumping nets several times into the water before lifting the material on board. It has to be ensured, however, that fragile nets are not lost from the winch during this process. Another possibility is pre-cleaning with a pressure cleaner in the harbour, where nets can be stretched out. This resulted in a better input material quality when tested with gillnet material by project partner KEST in Sandhamn harbour. If possible, hazardous materials such as large metal pieces, dead fish and lead lines shall be removed by fishermen or divers while cutting and storing the DFG in big bags. For the sorting process, a metal detector may help to improve the output of the rough-sorting.

Shredding
The rough-shredding of the rough-sorted material does not replace fine-sorting because of wear and ejection of the counter knife-triangles upon contact with larger

metal and rock fragments. It is important that the input material that enters the shredder contains less metal and rock pieces than remained in this trial among the rough-sorted net and rope material mix. The fine-shredding worked well for all fine-sorted materials from Sassnitz and Ahlbeck, for all previously rough-shredded materials from Sassnitz and Ahlbeck, and for the pre-sorted nets and ropes retrieved from wrecks.

Density separation

The density separation was very labour-intensive which created a bottle neck during this study. Also, residual lead fragments and sediments adhered to the polymer fraction which is why a clear separation of the toxic lead and the fine-grained sediment from the derived polymer fibres could not be achieved. However, there are automated systems for discarded fishing nets and agricultural foils which may be adapted to cope with lead and other hazardous substances which are not present in end-of-life fishing nets or foils. A density separation stage is also unavoidable to reduce the amount of residual sediment prior to further processing. All machine parts, including the friction washer discs, will be exposed to extreme wear when large amounts of residual fine-grained or coarse sediment are present, leading to extra replacement and repair costs. Extrusion in particular requires the residual sediment content in fibres to be very low, as the granulate will be breakable and impurities would lead to inhomogeneous properties of the output recyclates. For industrial processing of DFG, density separation is therefore crucial to remove both toxic lead contamination as well as sediments affecting extrusion and recyclate material properties.

Washing

The washing requires a different machine setup to prevent blockage between the feeding unit and the friction cleaning unit. In addition, there was some contamination from the previous use of the machine affecting the purity and smell of the output material. In particular, the friction washer is rinsed with hard plastic fragments, potentially made of PVC, which might have contributed to the high chlorine content found during chemical analysis (see Sec. 4). The polymers used as a washing agent would also have to be evaluated with regard to their ecological impact. Apart from some chemicals applied to treat the water, the washing is a "circular" process. However, the washing water has to be replaced when sufficiently contaminated and ecological impacts from the water disposal need to be considered. A final drying stage would be needed to extract the residual humidity, as would be required for the next step - polymer re-granulation.

Grinding

A preliminary grinding test with pure rope material led to a fibre fraction with 4-6mm fibre lengths. The shorter fibre length improves the pourability and might facilitate the re-use of DFG fibres in extruders for re-granulation and injection moulding. The usability of this fine-sorted rope material for injection moulding is currently tested for consumer goods production.

Table 2.3: Material flows of all processing stages applied during the pre-processing, shredding and washing trials at Vecoplan AG. Constraints in the experiment setup caused limited access to weight measurements, e.g. of the floating or bottom fractions in the density separation tanks (unknown values indicated by –).

Process	**Flow / Stock**	**Material Name**	**Value [kg]**							
			Fine-sorting				**Rough-Sorting**		**Pre-Sorting from wrecks**	
			Sasnitz Ropes	**Sassnitz Clean nets**	**Sassnitz Dirty nets**	**Ahlbeck**	**Sasnitz**	**Ahlbeck**	**Ropes**	**Nets**
Fine-Sorting	Input	DFG	450			85				
	Output	Non-Ropes & nets	127			17				
	Output	Fine-sorted	62	52	150	66				
Rough-Sorting	Input	DFG					277	783		
	Output	Large metals					4	53		
	Output	Big Bags					2	13		
	Output	Rough-sorted					-	-		
Rough-Shredding	Input	Rough-sorted					-	-		
	Output	Magnetic materials					16			
	Output	Rough-shredded					243	706		
Fine-Shredding	Input	Fine-sorted, Rough-shredded and pre-sorted	62	52	150	66	243	706	440	60
	Output	Magnetic materials	<<1	<<1	<<1	<<1	<<1	<<1	<<1	<<1
	Output	Fine-shredded	-	-	-	-	219	678	-	-
	Stock	Fine-shredded	0	0	0	0	203	386	312	0
Density separation 1	Input	Fine-shredded	-	-	-	-	16	292		
	Input	Water	400	700		700	800			
	Input	Salt	125	175		175	225			
	Output	Solution 1	300	400		600	-			
	Output	Bottom fraction 1	22	-		12	-			
	Output	Floating fraction 1	-	-	-	-	-	-		
Density separation 2	Input	Floating fraction 1	-	-	-	-	-	-		
	Input	Water	-	-	-	100	50	600		
	Output	Solution 2	-	-	-	-	-	-		
	Output	Floating fraction 2	-	-	-	4	<<1	18		
	Output	Bottom fraction 2	-	-	-	-	-	-		
Washing	Input	Bottom fraction 2, Fine-shredded	-	-	-	-	-	-	-	-
	Input	Water & Chemicals	-	-	-	-	-	-	-	-
	Output	Solution	-	-	-	-	-	-	-	-
	Output	Sieve fraction	-	-	-	-	-	-	-	-
	Output	Flotation	-	-	-	-	-	-	-	-
	Output	Washed fibres	33	37	111	0	0	54	62	66

3. Processing obstacles and solutions

In the following sections, the specific problems encountered during the processing tests of derelict fishing gear will be summarised. If known, potential solutions and further developments that would improve the work flow towards a recycling-oriented treatment of DFG will be discussed.

3.1 Pre-sorting limitations

Derelict fishing gear entering automated cutting and shredding machinery needs to be free of potentially damaging items. When retrieved from the sea, large metal fragments such as anchors or metal chains are regularly encountered. Stones become entangled when nets are moved across the seafloor through current motions. All of these materials are potentially damaging to various parts of the shredding machines. In addition, cutter blades will become blunt and fissured rapidly if these materials are included. One particular problem encountered with the Vecoplan shredding rotators, where counter-triangles on the rotator barrel work against counter blades, was the expelling of triangles at their pre-built breakage points. While these breakage points are deliberately included in the design of the shredding machine, the triangles might be bend or fissured and need replacement or at a minimum re-bolting when stones or larger metal items caused damage. This process is manually labour-intensive and costly.

Prior to shredding and cutting, the DFG therefore has to be sorted manually to extract and remove large, solid items with a size of more than 10-20cm. A pre-shredding test of the material in a coarse shredder with a sieve size of 200mm, leading to 20cm fragments, did not improve the material consistency sufficiently to be useful for fine-shredding (see also Sec. 2). In this case, rocks and metal fragments also caused expelling of counter-triangles despite the generally coarser setup of the more material-tolerant machine. The manual removal of large items takes up a significant amount of the processing time because of entanglement in the net material.

Fig. 3.1: Manual pre-sorting of DFG lifted with a crane to facilitate access. Metal items, canisters, and rocks were manually removed to avoid machine damage during shredding.

Limitations: The pre-sorting is time-consuming and physically intense labour. If carried out in the shredding plant or technology centre, the heavy items need to be transported from the harbour to the processing plant, increasing the total weight of shipments substantially. Technology centres and shredding facilities are not equipped to pre-process materials. Even if lifted by a crane, as was done at Vecoplan Technology Centre, the manual cutting tools and the experiences do not exist for an efficient pre-sorting process - because these centres are not are not customised for the processing of fishing net material.

Solution: It would therefore be desired that material is pre-sorted on board or at the harbour immediately after retrieval. An extensive collection and sorting procedure is carried out at Smögen Harbour in West Sweden, where end-of-life fishing nets are regularly processed. The sorting operations are organised by the local fishermen association FF Norden, but collection extends to numerous other ports in the Northern countries. A recent trial with retrieved DFG provided by the Municipality of Simrishamn as the local MARELITT Baltic partner was unfruitful because of the large content of other litter items entangled within the retrieved fishing gear. The material from this trial could not be prepared and forwarded to the recycling facilities for discarded fishing nets. The advantages of pre-processing in harbours are 1) that only a small fraction of the retrieved material by weight needs to be shipped to the processing plant, and 2) that fishermen are the most experienced and skilled in dealing with fishing net materials. A streamlined system would need to include this manual pre-sorting step after DFG retrieval from the sea in close collaboration with the harbours and local fishermen.

3.2 Shredding process obstacles

Obstacles in the shredding process include the large metal items and stones discussed above, but also the cutting and shredding of the net materials themselves. While ropes and lines are easily processed in the shredder, knots might not be broken up during the shredding process. In the following cleaning stages, these knots will be potential attractors for sediments, and might also limit the capacity of the fibre flow through the friction cleaner.

Coarse shredding limitations: One attempt was made to avoid the extensive pre-sorting step by using a coarse shredder prior to fine-shredding. The results are presented in Sec. 2. The problems encountered were the expelling of counter triangles and damage to the shredder blades, as discussed in the previous section. In addition, the material was not fit for fine-shredding after processing into 200mm fragments. Net and rope fragments were heavily entangled, and larger fragments of rock and metal were still contained inside the netting material after coarse shredding. When this material was introduced into a high-density saline swim-sink bath with the aim to remove rocks and metal items including toxic lead fragments, the material sank to the bottom immediately. Density separation of this coarsely shredded material was not possible, such that coarse shredding did not facilitate material preparation for fine shredding, which would have required these items to be removed.

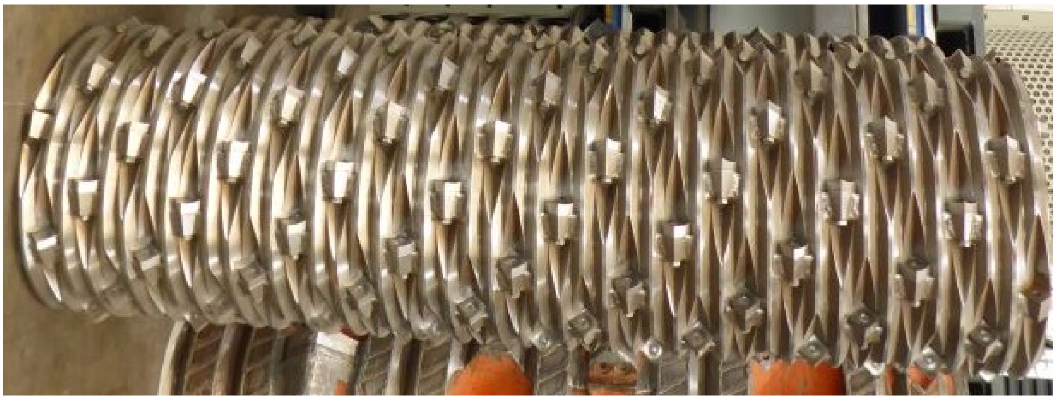


Fig. 3.2: The rotator drags the material into the cutting unit and the triangles form the counterblades to the cutting knives. Triangles are fixed with bolts for easy replacement, and will be expelled if large metal items or rocks are encountered. Without pre-sorting, damage to counter-triangles and cutting blades would require frequent and expensive replacements.

<u>Fine shredding & limitations</u>: Fine shredding works well once larger items were manually removed. It is sometimes difficult, even when material is lifted with a crane and suspended for inspection, to see sturdy items embedded in netting or between ropes. Particular care has to be taken when cables or ropes with steel cores are included in the material mix. The sturdy metal content is not always visible in this case. When bulky items are removed, shredding to a grain/fibre size of approximately 20-40mm was feasible and beneficial to further processing. The major limitation was faced when shredding gillnets. While the magnetic separator extracted small metal fragments such as fishing hooks efficiently, lead weights used inside the sink lines could not be removed. Fine-shredding causes these lead weights to be ground into small pieces, which possibly contaminate all further processing steps with lead. Density separation has to efficiently remove the lead fragments, however, when embedded inside the lines, a clean separation is not possible (see next section). Hence it would be desirable to remove lead lines/sink lines from gillnets before processing. While this is regularly done in harbours with discarded fishing nets due to the high cost and value of the lead lines, the sink lines were so heavily entangled in the monofilament netting when retrieved from the sea that prior removal was not feasible and had to be given up during the pre-sorting attempt.

3.3 Density separation limitations

In principle, density separation in a swim-sink bath is an efficient means to separate plastic fragments with characteristic densities of 0.9-1.3 g/cm^3 from high-density materials such as sediments and glass at 2.5 g/cm^3 and metal items including lead at 11.3 g/cm^3. For lost gillnets, the separation from lead fragments is crucial to avoid toxic contamination of recyclates and machines, while for trawl twisted lines and ropes the reduction of fine-grained sediment content is desirable to reduce wear and blockage of machine surfaces, cutting edges, and pipes. In addition, a large weight fraction of silt and lead contaminates the cleaning solution of the friction cleaner requiring regular exchange or extensive processing of the washing water.

While density separation in swim-sink bathes works well for granulated materials, such as sediments and plastic granules, the fibre material of retrieved DFG forms agglomerates and is particularly prone to entanglement of contaminants in the fibre structures. Several problems were encountered during the density separation bathes, which are discussed in the following sections.

Purity of the saline solution: In the Vecoplan experiments, de-icing salt was used for cost efficiency and availability of large amounts. Sufficient salt was applied to the 600l of water in a 1000l tank to achieve saturation density. However, de-icing salt is highly impure and contains substantial amounts of contaminating fragments such as fine grains, silt or other salts. When dissolved in water, these contaminants prohibit that the saturation density of 1.20 g/ml is reached. Impure solutions might reach densities between 1.10 and 1.15 g/ml. It was tested with a PA6 test block that PA6 would float on the solution. However, if PA6 netting was contaminated with other substances, floating of the fibres might not be expected. This limitation causes a potential loss of the target fraction, and would impede the extraction of heavier polymers such as PET or PVC with densities of up to 1.3-1.4 g/cm3 if present in the material mix. This might explain why a substantial fraction of material was lost during the swim-sink bath in high-density solution, as ropes were shown during the analysis in retrospect to predominantly consist of PET, which was not previously expected from material information on fishing nets.

Embedded & mixed materials: In the sink lines, small lead bars with diameter 5mm and length 30-40mm or lead spheres of diameter 3-4mm are embedded as weights in PP/PE twisted strands. These weights cannot easily be removed during manual sorting, as they are interwoven into the lines. Likewise, the lines were found to be heavily entangled with the monofilament netting and could not be cut from the bulk. The lead fragments cause the sink line fragments to sink in saline solution, as is their original purpose. This prohibits the re-use of the polymer material from the sink lines. However, this also implies that the bottom residual will be a mix of fine sediment, pebbles, polymers and lead and will therefore be toxic waste.

Solution: As lead is a valuable heavy metal and can easily be molten at low temperature and be shaped for re-use, an automated swim-sink separation needs to incorporate a methodology to extract the lead fragments from the sediments. This can easily be done after the swim-sink stage when the sludge is extracted from the tank e.g. by pouring the sludge through sieves retaining lead and pebbles. Fine-grained sediments would pass, which would largely decrease the sludge volume. The sludge would need further processing to extract the lead from surrounding polymer lines. Pebbles would be removed during the melting stage as residual sediment. Such a process would need to be developed especially when larger amounts of gillnets are to be retrieved, as expected within the MARELITT Baltic project in Swedish and Polish waters.

Fig. 3.3: Top panels: The fluffiness of the fibre material impedes complete density separation of the mixed materials. Residual sediments cause the saline solution to become dirty, affecting the density. Bottom panels: Bottom sediment contains silt and fibres entangled with other materials, including sheathed lead lines (middle of lower right panel).

<u>Fluffy PA fraction</u>: Trawl nets twisted from fine polyamide fibres display a tendency to "fluff up" during the shredding and cleaning processes. These fibres are very soft and lead to the formation of "fluffy furballs" which resemble raw wool or cotton balls. Within these fluffballs, sediments, wood fragments, but also other polymer fibres from the mx can be embedded and will not be released during density separation. Potentially, some of these artefacts will even adhere to the dense fibre agglomerates and "survive" friction cleaning. This implies that in PA-dominated material which is not monofilament but composed of fine fibres, a large percentage of residual contamination with other materials, including other polymers, is expected.

In addition, when small lead fragments are persistent in the mix, e.g. because gillnets and trawls are entangled in the retrieved DFG, the high-value PA polymer fibres will sink in the density separation bath and cannot be extracted. This intrinsic property of the PA fibre fraction complicates the separation of both the different polymer fractions as well as organic contaminants and lead.

<u>Solution</u>: There is currently no solution at hand other than an extensive pre-sorting and extraction of the materials, which is even difficult because PA is not always easily distinguished from other twisted polymer fibres when used in ropes and lines. One method that would need further testing is the final extraction of PA

through fine-grinding. If residual material is ground to a grain size of 2-4mm, the fibres become pourable and lose their fluffiness. This would, however, require an additional swim-sink bath for PA6 to be extracted from other materials after grinding. Currently no technical solution exists for how to deal with the wet polymer meal and how to extract the different fractions in such a hypothetical process. Alternatively, polymer identification with an IR spectroscopy pistol might support the pre-extraction of PA and other polymers during pre-sorting. As no material identification was available at Vecoplan, this would need to be tested for efficiency.

Separation of polymer fractions: Without spectroscopic material confirmation, it could not be tested how efficient the 2-stage swim-sink process was in separating PA from the low-density PP/PE polyolefin fractions. In particular, as the first analysis yielded a substantial PET contribution in ropes, density separation might lead to a PA/PET mix in the high-density fraction sinking in pure water in the second stage. The density separation would need further automisation and fine-tuning with a monitoring of the solution densities to ensure a cleaner separation of the involved polymers.

Automisation of density separation: One of the major time and effort limitations during the DFG processing tests at Vecoplan was the manual sieve extraction of fibres from the two swim-sink bathes. Two-stage density-separation tanks exist in end-of-life net processing plants, such as available at Plastix DK. Similar applications are built by Vecoplan for other uses, e.g. foils and similar polymer fragments. The efficiency of these automised density separation processes would need to be tested on lost fishing gear, where the high contamination with organic matter and sediments affect the solution density and cause rapid impurity of the tanks.

A different approach avoiding density separation in high-density solutions and possibly increasing the efficiency in material separation would be the infrared spectroscopy or laser detection of polymers. These techniques are routinely used in recycling plants to separate shredded plastic fragments into their various polymer types. Whether this process could be applied to the interwoven fibre mixes present in lost fishing gear needs to be shown. The advantage would be that highly efficient material separation with low loss and fault rates could be achieved in an automated way.

3.4 Cleaning process obstacles

Friction cleaning proved an efficient washing process especially for monofilament gillnet material. All other materials faced problems in the Vecoplan friction cleaning setup.

Blockage of the pump filter: For PA, the fluffiness of the fibres caused the pump filter to be blocked. With the aim to avoid blockage, the cleaning solution was diluted from 10 volume % of fibres to 3 vol. %, which did not solve the problem.

This happened for pre-selected ropes consisting either of PA6 or PET, but also for all types of twisted-line netting. It is to be expected that all of these materials contained at least a residual fraction of PA fibres, causing clumping that lead to filter blockage.

Solution: The friction cleaning stage can be set up such that no pump and filter is required. While such a setup has the need for a higher manufacturing hall and could not be tested in the Vecoplan facilities, friction cleaners with this setup are built regularly by Vecoplan and are well tested with a wide range of materials, including agricultural foils and other small-fragment compartments. It can therefore be expected that filter blockage can be removed if the friction cleaning setup follows the commonly applied fuelling from the top instead of a screw conveyor.

Purity of the cleaned material: After friction cleaning, the material was found to still contain a large amount of organic contaminants during analysis. This included shell and wood fragments, but also rubber pieces that might have been introduced during the processing (see next section). These contaminants prohibit the material as processed to this stage to be used in extruders for granulation. Hence, despite the extensive effort already undertaken to extract the polymer fraction and clean the fibres, all material mixes were still not fit for re-granulation and hence for re-use in moulding injection or other production processes. At this point, the material is not fit for recycling and a solution for the particular problem of residual contamination is not at hand. One testing angle might again originate from fine-grinding, after which the pourable fibres can be introduced into the extruder. Depending on the setup of the extruder, the melting process might lead to the expelling of residual sediment and hence an additional density separation stage leading to a higher purity of the polymer fraction. This, however, needs further testing.

Fig. 3.4: Left: Friction cleaning unit with pump and pipe on the lower-middle right. The catching tank flowed over as the pump filter became blocked by the fine fibres. Right: Small coloured and black particles can be microplastics included in the fishing nets, but might also originate from scrubbing and previous cleaning runs in the friction cleaning unit.

Introduction of impurities from previous processes: The friction cleaning machine is rinsed of materials from previous cleaning runs by sending fine-grained microplastic fragments with the washing solution through the pipes, friction discs, and chambers. While this ensures abrasion of unwanted substances from the cleaner walls, it can also cause residual microplastic fragments to be introduced into the fibre material. In addition, the crevices of pipes, tanks, and transportation units might evade this scrubbing process and contain residual materials from previous cleaning runs. In the gillnet material mix collected near Ahlbeck, rubber particles were embedded in the shredded and cleaned fibres. As rubber was not present except as mantling around cables mostly found in trawl netting, the detected rubber particles were likely introduced during friction cleaning.

Solution: A rigorous cleaning effort would minimise contamination by both scrubbers and residual materials from previous cleaning runs. However, such an effort might not be realistic regarding time and cost effort or even technically feasible as it would require taking apart at least several units of the cleaning machine. Hence, a certain amount of residual contamination introduced during the cleaning stage should be expected, and the cleaning process might be timed in such a way that the previously processed materials do not substantially impact the material purity and quality when introduced into the fibre mix.

Summary & overview of limitations & requirements for future DFG processing:

- Sediments cause abrasion and over-excessive wear on cutting and grinding machinery (see also Gerke et al. 2016).
- A density separation stage needs to be incorporated to remove lead fragments and reduce sediment load.
- Washing quality has to be improved to remove residual sediments.
- Manual removal of metal fragments and sink lines is time-, cost- and labour-intensive, but some form of manual processing is necessary to allow shredding, washing and granulation.
- Degradation in saltwater causes polymers to become brittle (Gerke et al. 2016), yet this might be overcome by using a suited pristine polymer matrix as the base material with recyclates as additives.
- Pre-sorting & separation into individual net and rope fractions and materials facilitates processing and re-granulation and increases recycling options for individual DFG fractions.

4. Analysis of physical and chemical properties of DFG

In order to evaluate the re-usability of DFG, especially retrieved fishing nets and ropes, in a circular economy approach, the material content and properties need to be investigated. Plastics contain a wide range of additives such as persistent organic compounds used as softeners, emulgators, flame retardants, etc. to achieve the physical properties desired for each plastic item. Some of these substances are known to cause medical harm (BPA, PCB, and other compounds), which were demonstrated to have endocrine impacts on mammals, marine and freshwater fish species in trials (Oehlmann et al. 2008, 2009, Talsness et al. 2009, see also Reifferscheid 2017 p.27 for a recent summary of experimentally confirmed adverse effects in freshwater species). The disruption of normal gender development of juvenile fish as a consequence of the endocrinic effects has led to the expression "endocrine-disruptors" for these substances. While the impact on human health is still a matter of intense research, the most profound results were derived on PBA leading to a publication by the German Federal Environmental Agency (UBA) on the health risks especially for children (UBA 2010). In addition to intrinsically applied additives to enhance material properties, plastics can take up toxic substances from the environment. In particular, plastics are known to adsorb and absorb toxins and contaminants such as persistent organic compounds from the surrounding seawater (Mato et al. 2001, Teuten et al. 2009, Holmes et al. 2012). These toxins are transported and released when plastic items remain in the sea (Teuten et al. 2009), but will be extracted when plastics such as nets and ropes are removed. Uptake has been shown for microplastic particles, which are particularly sensitive because of their large surface area. The fibre structure of fishing nets and monofilament lines implies that DFG has a large surface area as well, which is equally prone to absorb potentially harmful substances from the marine environment. If these fibres are to be re-introduced into the production cycle as pellets or granules and shaped into everyday products, it needs to be confirmed that their composition is non-hazardous for employees working with these materials and especially for consumers using these products.

After the processing of DFG, a chemical analysis including tests against hazardous substances following the EU REACH guidelines was carried out. As the use of softeners and other additives is not common in monofilament lines and other polyamide netting, special emphasis was led on contamination with heavy metals that might have been absorbed from the sediments. As the next step would be the production of pellets or re-granulation of the material in extruders, physical properties such as the melt index, flow characteristics and fracture properties need to be known. These properties allow the evaluation of the material for use in injection-moulding or granulate extrusion to allow re-introduction into the production cycle.

Material analysis was carried out with the following aims:

Derive the chemical composition of DFG, including:

- Polymer types
- Contamination with additives (softeners, flame retardants, ...)
- Contamination with toxins ab- or adsorbed from the marine environment or attachments such as sink lines (lead, cadmium, mercury, other toxic substances)

Derive physical properties:

- Melt index
- Flow characteristics
- Fracture properties
- Breakage endurance to external pressure forces

4.1 Preparation of derelict fishing gear for analysis

As described in the introduction, derelict fishing gear is not an easy material to process. Even after the shredding and cleaning and removal of metal fragments, processing of the material remains challenging. For chemical and physical analysis, the fibre compounds need to be homogenised (*compounding*) and test specimens have to be produced through melting and pelletisation in a pelletising extruder. Most extruders require pourable material to allow for a homogeneous flow and melting process.

After shredding and cleaning, DFG composed of nets and ropes has a fluffy, almost woolly consistence. Especially the fine polyamide fibres used in woven netting fluff up during the cleaning process and form conglomerates with other substances including PP/PE polymer fragments, but also residual organic matter not removed in the cleaning stage. These materials cannot easily be homogenised, and only few extruder setups exist that allow the use of fluffy fibreballs as influx material.

One option to increase the pourability of the DFG fibres is the fine-grinding described in Section 2.3.7. Fine-grinding to a grain size of 4mm was tested on pre-cleaned rope fibres and led to very soft fibre dust. The extrusion process was tested on this particularly uniform fibre fraction. With mixed materials still containing residual fine-grained sediments such as clay, as is common in the Baltic Sea, the grinding machine would wear down rapidly if larger amounts of material were ground. At the same time, fine-grinding takes substantially more time than shredding to 20mm grain sizes. For 20kg of rope fibres already pre-shredded to a fibre length of 20-40mm, exposed to a 2-stage swim-sink bath in saline solution and water, and cleaned in the friction cleaning machine, fine-grinding took more than one hour. This renders fine-grinding of larger amounts of netting and ropes not feasible with the currently available grinding mills. It is clear from this test run that grinding would improve the pourability and facilitate the production of test specimens from DFG samples for chemical and physical analysis.

Fine-grinding would also improve the possibilities for material re-use because granulation is a prerequisite for complete material recycling, e.g., through injection moulding. In addition to injection moulding, granules/pellets could also be re-introduced in the normal polymer production cycle, if granulation of DFG became feasible and common practice. In fact, the Danish company Plastix already uses end-of-life trawl nets in their re-granulation plant. The produced pellets are sold back to plastics producers for re-introduction in the normal production process (www.plastixglobal.com, www.plastixglobal.com/retrawl-in-brief/). Material processing is more challenging with DFG retrieved from the sea, as residual contamination with sediments and other substances is expected to be common as opposed to pre-sorted end-of-life netting. Hence a way has to be found to deal with both contamination and the difficult material properties before DFG can be analysed and fed into the recycling process.

Fig. 4.1: Gillnet material before and after friction cleaning. Prior to washing, large amounts of abrasive, fine-grained sediments are present. After cleaning, the polymer mix becomes visible.

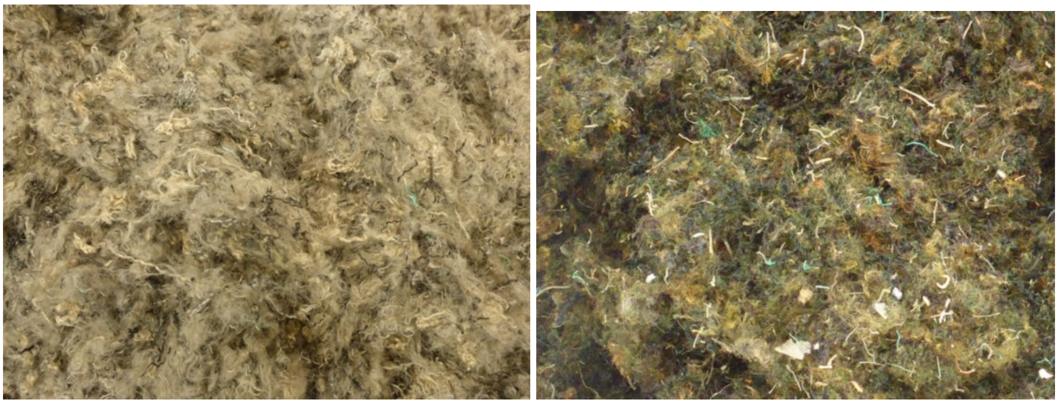


Fig. 2.2: Different types of retrieved fishing nets display varying mixes of polymer fibres after shredding and cleaning. Fluffy fibreballs indicate twisted polyamide lines as their origin. Individual fibres and monofilaments are still present in the mix.

Fig. 4.3: Fibres extracted from ropes before (left) and after friction cleaning (right), shredded and passed through a 20mm sieve (right image, left sample) and the same fibres fine-ground to a grain size of 4mm (right image, right sample) in order to achieve pourability for extrusion and regranulation.

4.2 Preliminary results

A preliminary analysis was carried out by the producer of granulation extruders Erema in Ansfelden, Austria, who designed and delivered extruders for the Chilean-Californian project and company "Bureo" for the recycling and re-use of discarded fishing nets. These nets are not retrieved from the Ocean, but are deselected by fishermen after reaching reduced durability at the end of their lifetime as fishing nets.

The chemical analysis revealed that the pre-sorted ropes retrieved from wrecks were predominantly composed of PET (Polyethylenterephthalat), a material not generally used in the fishing industry. For netting not composed of polyamide 6, the most common polymer types are PP and PE. PET is a high-density polymer with a characteristic density of 1.68 g/cm^3, substantially higher than the NaCl saline solution used for density separation, which can achieve a maximum saturated density of 1.2 g/ml. A significant fraction of the ropes and mixed rope-netting material processed at Vecoplan AG (see Sec. 2) sank during the swim-sink separation stage. Although ropes were not included in all test fractions, DFG retrieved in Sassnitz contained a wide variety of different netting materials including ropes of various thickness. If PET fibres were mixed into the overall fibre mix, and the fluffing of PA6 contributed to agglomeration of different polymer fibres, the incorporation of PET in the conglomerates would increase the likelihood of the material to sink in saline solution during swim-sink separation. In contrast to ropes, all 4 fractions of pre-extracted nets were predominantly composed of PA6 (technically PA6.0). This included twisted-line fishing nets of various line thickness as well as monofilament gillnets. PA6 was also a contaminating polymer in the PET ropes, while LDPE, PP, PS, Wood and Aluminium were present in the PA6 netting.

The residual abrasive fraction in all samples ranged from 0.1 – 6.3%. This fraction is expected to be composed of residual sediments. Washing led to a reduction of the abrasive fraction to 0.13 – 0.64% for all net materials, while PET ropes contained up to 6.3% of abrasive substances. Regardless of whether all of these abrasive substances originate from sediments or other composite materials inside the ropes, abrasion will increase wear of all machinery employed during the shredding, sorting, and cleaning stages.

Another quality indicator is the residual humidity present after the cleaning stage. In a full-process shredding-cleaning operation, a mechanical or thermal drying stage would be included at the end of the cleaning process. In the test facility at Vecoplan AG, a drying stage is not available, which led to large residual humidity content in the cleaned fibre fractions. After shipping to Erema, the residual content of volatile substances evaporating at 120°C, including water, was measured to be between 10% and 30% of the total weight. Twisted-line nets displayed residual humidities of 14-17% and the highest humidity contribution was found in monofilament PA netting with 31.2%. This seems surprising at first glance, as nylon monofilament is experienced as repellent to water in daily use. It is barely known that nylon is hygroscopic and can absorb 2.5-3.5% of water in the partially crystalline polymer structure even at standard humidity of 50% in air *(de.wikipedia.org/wiki/Polyamide).* Nylon immersed in water can absorb 10% of its own weight within 24 hours of exposure *(https://www.unitika.co.jp/plastics/e/nylon/nylon6/04.html).* In addition to hygroscopic absorption, twisted fibres and PA fluff will adsorb moisture because of their spongy structure. While this residual humidity after washing can be reduced during an additional drying stage, the embedded moisture in the crystalline grid changes material properties, decreases the melting efficiency during the recycling process and impedes test specimen production. In order to remove intrinsic moisture, a longer and potentially hotter drying stage would be required.

4.3 Chemical analysis of net and rope samples following REACH

Material properties of five net and rope samples were analysed in detail at the Magdeburg Polymer Service Centre (MAKSC). A chemical and spectral analysis provided the base polymers and a complete analysis following the EU REACH[2] guidelines (EC 1907/2006) was carried out to identify contaminants and potential toxins that might affect re-use of granulates produced from DFG. Physical and mechanical properties relevant for granulation/extrusion and potential applications such as injection moulding were derived for comparison with recyclates from discarded fishing nets and literature values.

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[2] REACH: European directive EC 1907/2006 on the ***R**egistration, **E**valuation, **A**uthorisation and Restriction of **Ch**emicals*

The details can be found in the complete report by MAKSC on the MARELITT Baltic webpage[3], and only the major findings are summarised here.

4.3.1 Procedure

The five samples contained nets and ropes retrieved in the area of Sassnitz/Rügen, ropes and nets collected from wrecks earlier and pre-sorted in a manual sorting facility in Poland, and one gillnet-dominated sample retrieved in Ahlbeck. While the Sassnitz samples contain a wide mix of materials including trawls, ropes, gillnets as well as metal fragments and other marine litter, the fifth sample from Ahlbeck was dominated by gillnets without trawl or thick rope contributions. This sample included the lead lines as well as the floats composed of PP-PE mixed materials, and hence is very diverse as well and not exclusively dominated by PA6.

For all samples, the basic polymer composition was determined through a thermal melting point analysis (DSC following DIN standard) and confirmed through FTIR spectroscopy. Mechanical properties such as tensile strength, elongation, impact strength and other characteristic physico-mechanical properties were evaluated using standard procedures. In addition, average material density, mass flow and volume rates were determined, as those parameters are relevant for injection moulding and extrusion into granules/recyclates.

In addition, a full contaminant analysis following EU REACH standard was carried out to evaluate levels of potentially harmful or toxic substances.

4.3.2 Basic polymer composition

Basic polymers were first determined from thermal DSC analysis, which reveals the major melting points. A first estimate of the base polymer of each sample was obtained through visual microscope analysis during melting. Polymer content was confirmed through FTIR material identification when it became clear that only the base polymers could be derived with DSC. As most polymer fibre materials from derelict fishing gear contain mixes, e.g. because of the presence of PP/PE floats in the shredded netting, swim lines with PP/PE lining, etc., a full FTIR material analysis was advised and might also be the method of choice wherever possible when evaluating polymer properties of DFG. The spectra can be found in the service report, and the major findings are summarised here. The gillnet-dominated Ahlbeck sample is used in Figs. 4.4 to 4.6 to illustrate the polymer content determination.

All fishing net samples including trawl and gillnet dominated samples from Sassnitz and Ahlbeck, respectively, and the pre-sorted nets from wrecks were composed of PA6 with PE, PP and PET as additional compounds. The ropes appear to be produced from more diverse polymer types. While the rope fraction extracted from the Sassnitz sample is based on PA6 with PP and PET additions, the pre-sorted ropes from wrecks are dominated by PET with PE and PA6 contributions.

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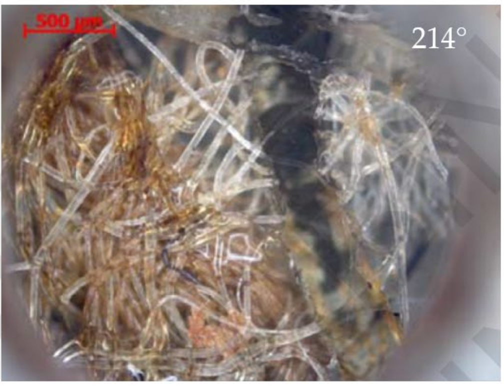
[3] https://www.marelittbaltic.eu

It is interesting to note that both nets and ropes are composed of PA6 or PET, which have higher densities than water and hence neither nets nor ropes are intended to float. This is different for the swim lines into which the floats are embedded – those are typically produced from PP or PE or a PP-PE mix to be lighter than water. As all of these contributions are expected to be present in retrieved fishing gear when individual parts cannot be disentangled, it is no surprise that all of these fractions are also found in the mixed materials retrieved in Sassnitz and Ahlbeck. However, floats had been removed from the nets and ropes pre-sorted by the Polish manufacturer, such that the mix of materials in this case indicates that ropes and nets are not always produced from single-type polymers. As in plastics packaging, this complicates the recycling process and decreases the options for material re-use.

A secure pre-determination of the base material during the sorting process would increase the options for recycling and cause derived granulates to have a higher degree of purity. For instance, the determination of polymer types with hand-held IR sprectrometers would facilitate material sorting before the extrusion into granules.

Pre-washed gillnet sample (Ahlbeck)



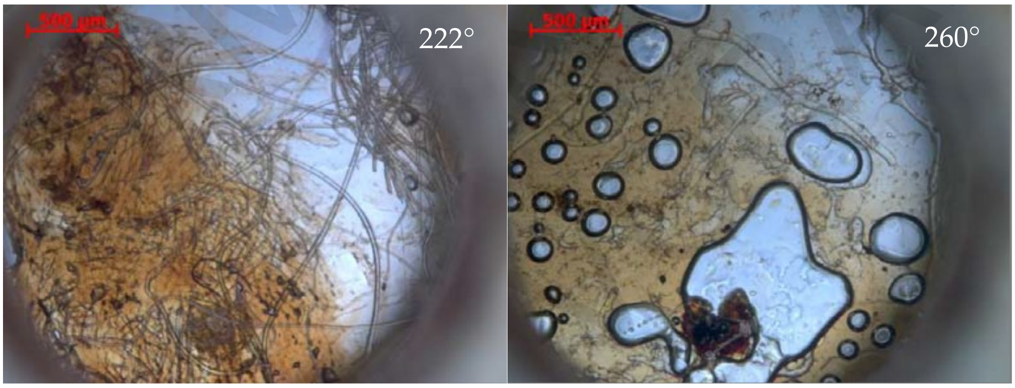


Fig. 4.4: Pre-washed Ahlbeck gillnet sample (raw, top left) and visual microscopic analysis of polymer content: a) at room temperature, b) at 167°C, c) at 214°C, d) at 222°C, e) at 260°C, representing the consecutive melting stages of PP/PE at around 160°C, of PA between 214 and 222°C, and of PET as the most temperature-resistant polymer melting above 260°C. The visual analysis of all other samples can be found in the ***complete analysis report*** *(© MAKSC GmbH, Dr. Martina Lehmann)****.***

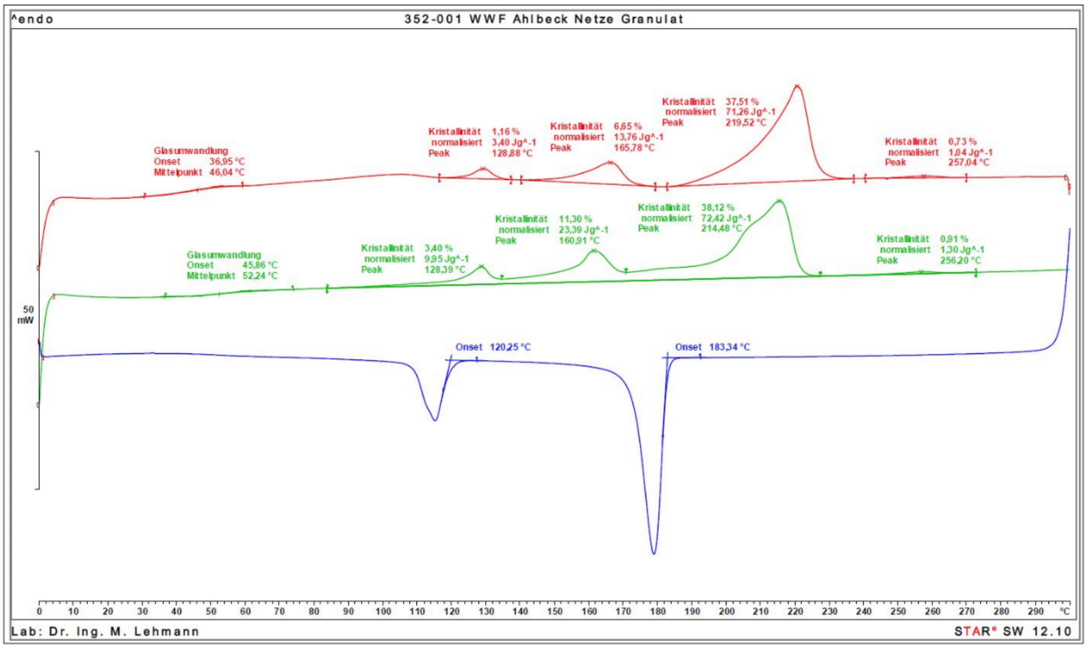


Fig. 4.5: Example of DSC thermal analysis for Ahlbeck gillnets. The peaks display the melting temperatures of individual molecular components in the mixed material. The melting peak around 160°C corresponds to the PE/PP fraction, the peak around 214-220°C corresponds to the PA melting peak (© MAKSC GmbH, Dr. Martina Lehmann).

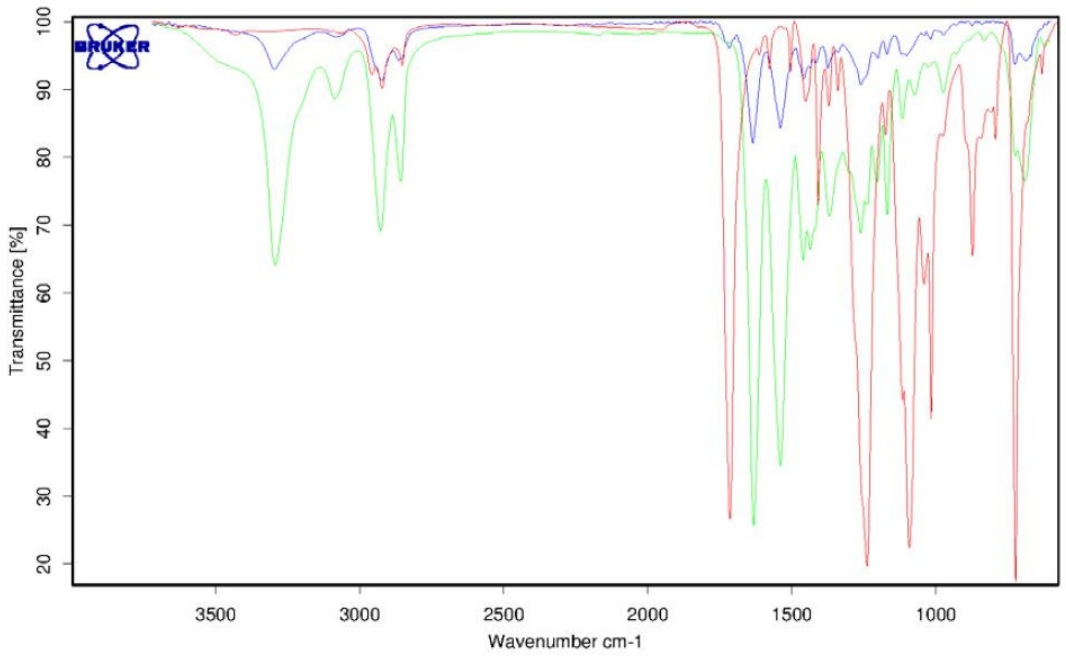


Fig. 4.6: FTIR spectra of Ahlbeck gillnets (blue) in comparison to PA (green) and PET (red) template spectra. (© MAKSC GmbH, Dr. Martina Lehmann).

4.3.3 Toxic contaminants

It is well-known from fish and mussel analysis that heavy metals are omnipresent in the marine environment. This is expected to have improved in the Baltic Sea since the ban on crude oil for shipping. In the past few years, plastics have been found to adsorb toxins from surrounding seawater. While this is not scientifically confirmed for heavy metals, it is a known issue for additives such as phthalates and other potentially harmful or endocrine active substances.

In most samples, mercury, chrome and cadmium are either below the detection threshold or found at relatively low concentrations. Antimon is detected at low to moderate levels. Lead, however, is detected significantly above the detection threshold in all samples, although concentrations vary substantially. The highest lead concentration is found with 358 ppm in the gillnet sample retrieved in Ahlbeck, which can be explained by the large amount of lead lines entangled in the netting. A concentration of 358 ppm implies 0.3 g of lead per kg of processed and cleaned material. However, this material was already shredded and processed through density separation in a 2-stage swim sink bath and a friction washer. The raw material prior to processing contained 27.4 g/kg of lead (see Sec. 5.1), implying that most of the lead was extracted during density separation as anticipated. This implies that either manual removal or density separation are required to render DFG composed predominantly of gillnets recyclable.

The pre-selected ropes and nets from the Sassnitz mixed sample during fine-sorting, on the other hand, do not display comparably elevated lead contents. Here the lead concentrations of 10 and 26 ppm are below the limiting value of 100 ppm required in the EU packaging directive (Art. 11 in **94/62/EC**). However, in the pre-sorted rope and net samples processed at the polish manufacturer, all sink lines were previously removed and yet, the lead concentrations are comparable to the gillnet sample. This is surprising in view of the fact that all metal fragments had been manually and thoroughly removed from these samples. The lead might actually originate from the Ahlbeck sample which was shredded prior to the pre-sorted samples, which did not need to be density separated and cleaned and hence were processed last. The concentrations were similar to the gillnet sample, suggesting that lead contamination in machinery is high and that special care has to be taken to remove abrasive lead fragments from the processing surfaces. The reason for such contamination might be found in the softness of lead as compared to other metals.

From the three halogens part of the REACH analysis, fluorine, chlorine and bromine, only chlorine showed elevated concentrations, which were above 1000 ppm or 1 g/kg in several samples. The origin of this contamination could not be resolved. One source of chlorine could be PVC, which is not used in fishing gear. The friction washer at Vecoplan AG is regularly rinsed with hard plastic particles. Although personnel confirmed that special care is taken to remove residual fragments from the washer unit, it cannot be excluded that some of the PVC fragments entered the samples. A contribution of 0.27% by mass would be sufficient to explain the contamination level. This would also explain some colourful fragments observed among net fibres. This is the only potential source of chlorine that could be identified, and it would also explain why chlorine is enhanced in all samples, albeit with concentrations of 221 to 1421 ppm not at the same rate (see MAKSC analysis report for details).

A limiting value of 400ppm is recommended for steel machinery as higher chlorine concentrations might increase corrosive effects on machine parts, which was fulfilled by only one of the five samples. Corrosion protection might therefore also be an issue for extrusion and other processes in steel-based production units. If the contamination is caused by the rinsing particles of the friction cleaner, this could be resolved by more thorough cleaning runs prior to fibre washing. In case the chlorine originates from paints or other contaminants and cannot be avoided through processing improvement, corrosion needs to be considered for all fibre processing steps.

Common polymer additives investigated under REACH, such as alkanes, Bisphenol A and flame retardants, were not identified within the detection limits in all samples. Phthalates were detected yet with low concentrations on the order of a few ppm. Polycyclic aromatic hydrocarbons (PAHs) showed surprisingly enhanced levels in both pre-sorted net and rope samples from wrecks. The origin of the PAHs is not clear. The material was retrieved from wrecks by divers with different techniques than used for the more recently dragged Sassnitz and Ahlbeck material. Also, the material was stored over extended periods of time in containers as well as in the Polish manufacturer grounds.

Hence contamination at any stage of these processes during the past 2 years since retrieval cannot be excluded. Therefore, it is not clear whether the enhanced PAH levels are related to fishing gear additives, to extended residence times in seawater especially near wrecks, or to the pre-sorting and storage process prior to analysis.

The different sources and levels of potentially harmful contaminants impede recycling of derelict fishing gear without careful analysis and pre-processing. A density separation stage allowing to remove lead fragments from retrieved gillnets is particularly crucial to remove excessively high lead concentrations found in the REACH analysis of the processed and washed fibres. The simplified manual density separation conducted during the trials was efficient in reducing lead content by a factor of approximately 10, but was not sufficient to bring lead contamination below the limiting values of the EU packaging directive. In addition, a full chemical analysis following the REACH classification must be recommended given enhanced levels of chlorine and PAHs before material can be processed for production and conversion into consumer goods.

4.3.4 Physico-mechanical properties

Physical and mechanical properties were determined to derive usability of DFG for standard recycling applications such as extrusion into granules, and are used for comparison to properties of recyclates produced from discarded fishing nets and the results of the rare recycling studies of fishing net and rope materials found in the literature. A few selected parameters are compared here with literature values, while the complete characterisation of the material properties can be found in the MAKSC report on the MARELITT webpage.

Fig. 4.7: Test specimen of Ahlbeck gillnet sample for mechanical strain tests (© MAKSC GmbH).

One set of comparison values originates from a recycling capability study of nets and ropes retrieved during the fishing for litter project initiated by the German nature protection organisation NABU. Experiments were carried out in collaboration with the University of Magdeburg-Stendal and results can be found in Gerke et al. 2016. Special focus was led on the comparison of sea-based and retrieved materials with new PE and PA6 nets and ropes to evaluate degradation during exposure in saltwater.

The second comparison baseline are the recyclates from discarded fishing nets and maritime products provided in the factsheets of Plastix Denmark. Plastix is a manufacturer working with end-of-life fishing gear and other products from the maritime industry. Five types of recyclates are provided, which are 95% dominated by post-consumer input according to the factsheets. Input materials are nets for NordIX rHDPE, nets, trawls and ropes for OceanIX rHDPE, maritime and fisheries ropes for OceanIX rPPC, post-use input materials for NordIX rPPC lightjazz and post-industrial input materials for NordIX rPPC white. The latter two PP recyclates are based on solid input materials such as fish boxes, while the three PE and OceanIX PP products are based on net and rope fibre inputs.

As the base polymers of the retrieved DFG were found to be PA and PET, the densities of the net and rope samples range from 1.09 to 1.31 g/cm^3. These densities are by definition higher than the density of water, while the comparison PP and PE polymers have lower densities around 0.9 g/cm^3 such that different physico-mechanical properties regarding melt flows and tensile strengths are to be expected. A direct one-to-one comparison is impeded by the fact that only rare information on material properties of fishing net recyclates are available.

Durability of granules produced from nets & ropes

Tensile strength and elongation at tensile strength or break point (OceanIX, NordIX) provide an indication of the durability of the material. Test specimen from MARELITT WWF net and rope PA6 and PET samples have tensile strengths in the range 23 to 56 Mega-Pascal, which are comparable to PP/PE values of 22-30 MPa in recyclates delivered by Plastix (Plastix product fact sheets 2017, www.plastixglobal.com). Elongation at tensile strength is at most a few percent in DFG samples, which is very low compared to elongation at breaking point measured to be 9-102% in the NordIX and OceanIX recyclates.

Impact strength before break measures the force that can be applied to a material before it fragments. With 4-25 kJ/m^2, the impact strength of our net and rope samples is comparably low. Impact strengths in test specimen generated from PE dolly ropes and net fragments from the fishing for litter project are measured to be 45 and 150 kJ/m^2, respectively (Gerke et al. 2016). The fishing for litter study finds that dolly ropes exposed to seawater degrade severely as compared to new dolly ropes with impact strengths of 164 kJ/m^2. Mixed nets, on the other hand, did not show signs of degradation in the impact strengths (new nets: 154 kJ/m^2, retrieved nets: 150 kJ/m^2). The authors suggest that the large surface area causes dolly ropes to be prone to weathering impact, while entangled nets might be more resistant to UV and wave exposure. The use of dolly ropes to protect trawls from bottom abrasion likely contributes to their rapid fragmentation. Nevertheless, tolerable impact strength is even higher for degraded dolly ropes made from PE as compared to all PA6 and PET nets and ropes investigated in this study. Specimen from the same polymer types would need to be compared to decide whether the low values of PA and PET indicate that the nets and ropes retrieved from the Baltic Sea lead to breakable products and are not suited for recycling. Unfortunately, impact strength is not provided in the NordIX and OceanIX factsheets, which would allow direct comparison between PE samples. The low impact strength in the higher-density polymer materials PA6 and PET might also reflect the hardness of the materials leading to lower flexure and lower resistance to breaking impact.

The melt flow index (MFI) is relevant for the melting properties of materials e.g. for the extrusion process when producing granules and for injection moulding in the production process. The MFI is measured in grams per 10-minute flow intervals, which implies that a high number means a high flow rate and hence higher liquidity of the substance. A higher melting rate facilitates a constant flow in the extruder and ensures a larger throughput as compared to low flow indices. The MFI ranges from 3 g/10min for pre-sorted nets to 43 g/10min for gillnet fibres. As both of these fibre samples have PA6 as the base polymer with similar mixing components, the difference cannot be explained by a difference in the predominant base material. The high flow rate of gillnet PA6 fibres suggests that gillnets would be particularly well suited for extrusion and injection moulding if the lead contamination could be removed properly. These MFI measurements provide another incentive to improve density separation and lead/metal removal to allow this high-value material to be recycled. By comparison, the flow indices of dolly ropes, mixed nets and OceanIX rHDPE and NordIX rHDPE polyethylen granulates are substantially lower at around 0.5 g/10min (see Table 4.1) which again might reflect the physical properties of PE as compared to PA and PET. The higher MFI values of 3 to 36 g/10min of the Plastix PP samples suggest that variation of the melt flow index in polymer types and even within a single polymer type can be substantial. The MFI values found for our PA6 and PET samples are in the same range as the Plastix PP samples, suggesting that melt flow is not a limiting factor for using retrieved fishing nets and ropes for material recycling.

After reviewing the analysis results, the question arose as to whether the extrusion process would mitigate the lead contamination e.g. by removing lead in the metal filter through which the melt flow is guided. For the Ahlbeck gillnet sample the resulting granulates were therefore analysed with respect to their toxic contamination level. During this analysis, polycyclic aromatic hydrocarbons were reduced by a factor of 3.5, while the high chlorine contamination did not change significantly. For lead a surprising increase in concentration by a factor of 10 was found. This increase in lead concentration is not understood. It suggests that lead was melted in the extrusion pipe and enriched at the base of the melt flow where granules were extracted, or that a fibre-fragment mix with particularly high lead fragment contribution by mass was accidentally chosen to produce the granules for test specimen. This implies that all physico-mechanical values derived for the gillnet sample have to be treated with caution. Again, removing the lead contamination would be required to derive more representative properties of PA6 gillnet fibres and decide on their suitability for material recycling. The results of the granulate analysis are available in the appendix of the MAKSC sampling report.

Table 4.1: Polymer composition and physico-mechanical properties of net and rope samples in comparison to granulates made from recycled fishing nets and literature values.

Sample	Base polymer	Add. Polymers	Density [g/cm3]	Tensile strength [MPa]	Elongation @ tensile str. [%]	elastic modulus [MPa]	Impact Strength [kJ/m2]	MFI [g/10min]
WWF Germany net & rope samples analysed for MARELITT Baltic								
Sassnitz Ropes	PA6	PET, PP	1.14	52.7	3.3	2630	7.8	20.9
Presorted Ropes	PET	PA6, PE	1.31	23.3	1.0	2597	4.3	15.2
Sassnitz Nets	PA6	PE, PP, PET	1.13	56.3	3.7	2635	25.2	8.7
Presorted Nets	PA6	PE, PP, PET	1.14	51.8	2.4	2800	13.5	3.4
Gillnets Ahlbeck	PA6	PE, PP, PET	1.09	27.1	1.5	2401	7.1	42.8
Fishing for Litter net & ropes samples analysed at the Technical University of Magdeburg								
Dolly Ropes	PE						45	0.50
Mixed Nets	PE						150	0.49
Ropes	PA							
Trawl Codend	PA							
Plastix market recyclates from nets, maritime ropes and post-use/post-industrial inputs								
NordIX rHDPE	PE		0.94	21	102			0.56
OceanIX rHDPE	PE		0.95	23	88			0.58
NordIX rPPCligh	PP		0.93	27	18			3.6
NordIX rPPCwhi	PP		0.92	22	9			36.1
OceanIX rPPC	PP		0.91	30	94			3.2
Singh et al. 2018 glass fibre – gillnet compounds								
Range in different types of compounds	glass fibre, PA6 layers			51–54		90–110		

Comparison to glass fibre – gillnet layer composites

A recent study by Singh et al. 2018 compared glass fibre with test specimen made from glass fibre and gillnet layers, presumed to be composed of PA. Layers of glass fibre were combined with layers of gillnet material and molten into test specimen.

In these trials, the gillnets were not converted into granulates first, but the fibre material of the gillnets was directly molten into composite layers. They find tensile strengths in the range 51-54 Mega-Pascal and elastic modulus between 90 and 110 Mega-Pascal for the composite materials, impact energy absorption of 50-56 Joule, and flexural strengths between 24 and 27 Mega-Pascal. The flexural modulus varied between 12.2 and 13.4 Giga-Pascal. Singh et al. conclude that glass fibre – nylon composites have higher elasticity and flexure as compared to pure glass fibre compounds, as expected from PA properties, while glass fibre is stronger as reflected in higher tensile strength, and recommend glass fibre-gillnet composites for the production of boat hulls for small traditional vessels. While tensile strength of the compounds is similar to the values found for fishing net and rope samples from MARELITT, the elastic modulus is lower by more than one order of magnitude as compared to all our specimen from fishing nets and ropes. The limited elasticity is likely a consequence of the use of more breakable glass fibre as the base material by Singh et al., and the fact that they do not process the fishing net into granules prior to specimen generation, such that specimen break with exposed net fibres during elastic modulus measurements.

4.3.5 Summary

Test specimen generated from nets and ropes retrieved from the Baltic Sea display comparable physical and mechanical properties to recyclates derived from end-of-life fishing gear and maritime materials. Final conclusions are currently limited by the fact that only PE and PP based recyclates are available for comparison, while retrieved nets and ropes are predominantly composed of PA6 and PET. As the mechanical properties of high-density polymers such as PA6 and PET are not expected to be directly comparable to low-density polymers such as PE and PP, a final analysis has to await the planned production of PA6 recyclates by Plastix Denmark. Nevertheless, it is reassuring to find melt flow indices and tensile strengths in the range suited for extrusion and recycling applications. The major limitation for the use of the retrieved nets is currently the high lead contamination level, which reinforces the conclusion above that lead fragments from sink lines need to be removed manually or through density separation techniques to render retrieved DFG fit for material recycling.

Evaluation of further use of recyclates

MAKSC concludes in their report that further use of all materials is theoretically feasible and is currently limited by the high hazardous substance content. Particularly strict are the rules for packaging materials following the EU packaging directive (94/62/EC). This can also be considered the strictest limit required to ensure consumer safety when products could be reached by small children. Cumulative contamination of heavy metals in packaging material is limited to 100 ppm, which is only achieved in the case of the Sassnitz net and rope samples. These samples were pre-selected from mixed materials with very little gillnet content. The elevated chlorine content of the Sassnitz net sample is a further point of concern, and future DFG recycling experiments should ensure measuring the chlorine as well as the lead contamination. With these elevated values, the material would not be suited for packaging, but might be well suited for products not in contact with food and not at risk of being in the hands of small children.

Technical improvements suggested by MAKSC to facilitate further processing into granules and end products include melting filtration with fine metal mesh filters to reduce residual metal, rock and wood fragments that were not removed during washing. Furthermore, the fibres need to be pre-dried for extrusion and subsequent injection moulding, and a finer grinding size of the fibres leading to a more compact input material with better pourability for easier influx into the extruder would facilitate granulation further.

The mix of additional polymers into the base material does not impede recycling applications, according to MAKSC recommendations. Mixed materials such as PA/PET or PA/PP are used in market products. However, for these products it is difficult to implement a circular economy approach as subsequent recycling is limited. The analysis did not provide mass fractions of the base material as compared to the additives and contaminants. The value of such evaluation is also limited given the diverse nature of the mixed derelict fishing gear retrieved. When sorting is carried out, future tests should be conducted with a focus on the mass fraction of the base polymer and the amounts of other contributions. Understanding the mix in each individual net and rope fraction would facilitate identification of applications.

One option to use the fibres is as a filling material in a well-defined pristine polymer matrix. The matrix material can deliver predefined properties while hosting a certain fraction of net and rope fibres such that performance is not compromised. These suggestions require further study with pre-sorted materials.

5. Thermal material processing

5.1 Introduction to thermal processing

The results of the chemical analysis have shown that polymer recycling of mixed DFG materials will be difficult unless extensive handling and pre-sorting is carried out. When pre-sorting is not feasible, thermal processing techniques might allow the use of the energy value of the polymer molecules while extracting lead and other metal components at the same time. Two existing technologies already applied for organic matter recycling are thermal processing in pyrolysis-type techniques and hydrothermal processing or “steam reforming”. Steam reforming can be described as a high-temperature process where organic waste is gasified into a hydrogen-rich synthetic gas. While air as a source of free oxygen is removed from both processes, steam reforming of dry materials requires water injection to provide the oxygen and hydrogen to break up polymer compounds into C and O or C and H gaseous molecules. The residual hydrogen is unbound in the process and left as an energy source in the synthetic gas. This process is also called "hydrolysis" by reactor producers, but note that this does not refer to the chemical hydrolysis reaction unbinding molecules by water which takes place under much lower temperature conditions and in different chemical environments. Steam reforming does require a humidity level of 25-30% to allow for organic molecule disintegration and reforming into an energy-rich output gas, which is ideal for derelict fishing gear prone to high amounts of water absorption.

A second reason to investigate thermal processing options is the high lead content in the raw material. After shredding and prior to any further processing, the gillnet-dominated Ahlbeck sample contained 27.4 g/kg lead, or about 3% of lead by weight equivalent to a concentration of 30,000 ppm (M. Krüger and LGU Environmental Laboratory, private communication). The limit to classify lead-contimated fractions as hazardous waste in Germany is 2.5 g/kg or 2500 ppm (Implementation notes for the attribution of wastes, Appendix IV, Table 1, Berlin 2015, Amendment 2017/997 to the European Waste Framework Directive 2008/98/EC). Hence the retrieved gillnet material is a factor of 12 above the threshold and must be classified as hazardous waste. Disposal of hazardous waste can be through incineration in the case that wastes are flammable or in hazardous waste landfills dedicated to hazardous substances, which is more likely for lead as a metal, e.g. in the highly concentrated residue after incineration of attached organic material. In any event, disposal is costly, at several hundred Euro per tonne of material, which can deter fishermen from bringing derelict, accidentally collected gillnets to shore. Disposal in deep landmines is not an ecologically viable solution, as it will place lead from one dumping site (the seabed) to another (deep soil or rock). As lead has a high economic value, a removal from the circular economy for metals would also be disadvantagous. One tonne of lead is traded at around 2,000 Euros on the financial market (Feb 13, 2018) and scrap lead is traded at 1500 Euro/tonne (http://www.schrottpreis.org/bleischrott/). The high market value of lead provides an additional incentive to process the gillnet material rather than to pay for hazardous waste dumping.

After density separation, the lead concentration in the gillnet-dominated sample was with 2.0 g/kg or 2000 ppm only marginally below the hazardous waste threshold, although 90% of the lead could be removed in the two swim-sink stages in saline solution and tap water. However, the fibrous structure and clumpiness of the material cause small lead fragments to be trapped in fibre balls. Another disadvantage was that polyamide sank in the second swim-sink bath, such that residual lead content was expected to be higher in the PA fraction than in the surface PE/PP mix. Friction washing apparently reduced the lead content in the PA fraction further by 80% to 358 ppm. It can be concluded that an industrial density separation strand with several stages would decrease the residual lead concentration substantially.

Although all lead concentrations were nominally below the threshold for hazardous waste classification after processing, density separation and washing, retrieved DFG from the sea in harbours will typically not be processed for economic reasons. In this case, the gillnet material has to be considered hazardous waste.

Fig. 5.1: Gillnet-dominated input material as retrieved at sea (© Andrea Stolte/WWF).

Pyrolysis and steam reforming offer two technologies that both allow to extract lead and other metal fragments and sediments from the material mix. During the thermal processing, the polymers as well as other organic molecules are split into natural gaseous molecules composed mostly of C, O, N and H. Pyrolysis ovens operate at lower temperatures between 400 and 800°C under exclusion of oxygen and water, while the hydrothermal reaction takes place at 1000-1300°C with 25% humidity. Low-temperature processes lead to the formation of a synthetic gas a fraction of which might be condensed into oil, but at these temperatures not all organic molecules are unbound and toxic emissions result from PA materials during pyrolysis, requiring special filtering or post-combustion techniques. During high-temperature thermal processing (steam reforming), all organic molecules are unbound and converted into a synthetic energy gas that can be used as input to the natural gas system or to extract the hydrogen becoming unbound in the process. Details of individual trials conducted with DFG can be found in each section below.

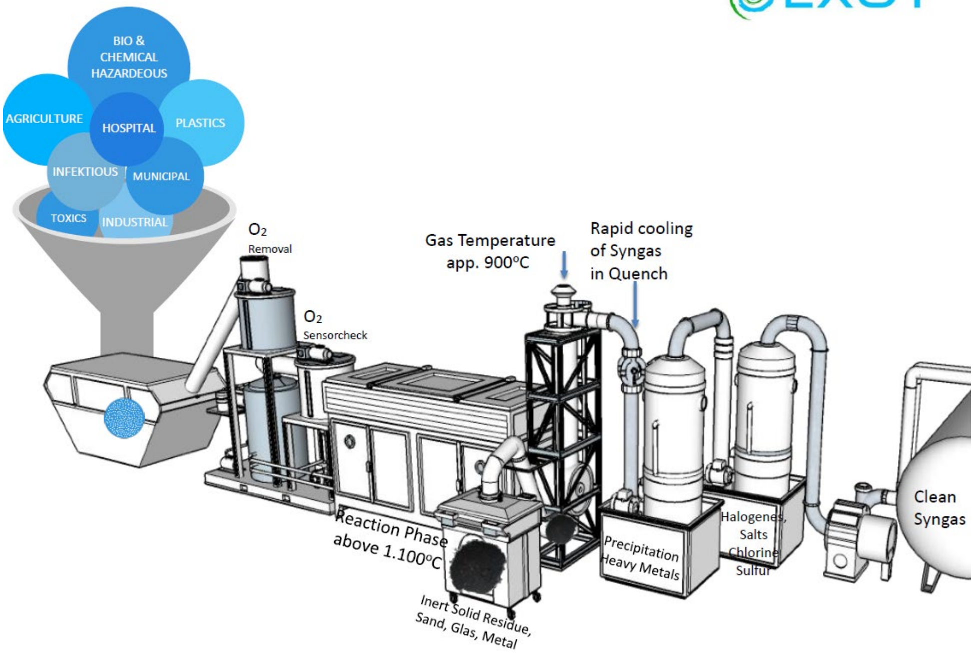


Fig. 5.2: Schematic illustration of EXOY's UHTH processing reactor in Freienbach, Switzerland. © EXOY

5.2 High-temperature processing (UHTH) of gillnets

5.2.1 Experiment setup

The company CleanCarbonConversion/EXOY based in Germany and Switzerland offered a steam reforming test run with DFG as the single input material in their facilities. In their technical descriptions, they prefer the term "high-temperature hydrothermal processing (UHTH)" to describe the steam reforming process (see also www.cleancarbonconversion.com). High-temperature hydrothermal processing of gillnets retrieved in Ahlbeck was carried out during a test run in the 5t capacity UHTH reactor at EXOY in Freienbach, Switzerland. Large metal pieces and other large waste items were manually removed prior to further processing. The material was pre-shredded using a 20mm sieve at Vecoplan AG in Bad Marienberg, yet fibres as long as 40mm could be transported through the circular sieve holes (see Section 2). Fibres longer than 25mm caused the feeding auger at EXOY to stall occasionally, which could quickly be resolved by a short reverse of the auger.

Fig. 5.3: Gillnet feed material used for thermal processing (left). UHTH processing reactor at EXOY's waste recycling facility in Freienbach, Switzerland (right).

Before entering the depolimerisation reactor, the material was flushed with nitrogen to remove air and hence free oxygen from the process. Water is normally fed into the hydrothermal process to provide hydrogen and oxygen for the conversion of organic materials into energy gas composed of the dominant fractions CO, CO_2, CH_4 and H_2. In the case of the fishing nets, the residual humidity in the PA6 fibres was 25% and provided sufficient H_2O for complete depolimerisation of polymers and organic residue.

In the energy balance, the liquidation and cooling of nitrogen used for flushing is not considered. For a full energy balance evaluation, the energy use for the provision of nitrogen would need to be included. This factor is ignored in the following results analysis, as energy use for nitrogen production was not provided.

EXOY send samples to Wesseling AG in Lyss for pre-analysis, which resulted in calorific values in the range 27,000 – 30,000 kJ/kg for both dry substance and organic substance contributions. The energy content of the material would also be sufficient for standard incineration plants requiring minimum calorific values of 10,000-18,000 kJ/kg in the dry substance (M. Krüger, Tönsmeier Recycling GmbH, private communication). However, the high lead content of 3-20% by mass causes the gillnet material to be classified as hazardous waste, which would have to be deposited in hazardous waste facilities. Hydrothermal processing, on the other hand, allows the conversion of the polymer material into synthetic gas while lead is extracted in the process as solid waste. The Wesseling analysis found a carbon content of 46% by mass in the ash available for synthetic gas generation, yet only 30% of the sample could be converted into ash, suggesting a total solid mass content of about 70% by mass in the single analysed sample. The solid component is likely a mix of sediments, lead and iron contamination from sink lines and steel fragments not pre-extracted during manual metal removal. The calorific heating values determined likely refer to the polymer content only after metal fragments were removed.

5.2.2 Technical details of the UHTH experiment

The hydrothermal reactor was operated at 1100°C leading to complete gasification of polymers and organic residue. In this temperature regime, long-chained molecules are disintegrated into basic substances such that no toxic emissions are produced. This is an advantage over lower-temperature pyrolysis techniques operating at a maximum of 800°C, where residual toxic emissions cannot be avoided during PA processing and exhausts require additional filtering techniques.

The melting temperature of lead lies with 327°C far below the operating temperature of the UHTH reactor. Hence lead melts during the heating process and is expelled and solidified in the solid waste auger.

The feedrate of the 5t capacity UHTH reactor is 100kg/h, and in the first experiment on Dec 5th, 2017, 138kg of shredded gillnet material were fed, while 174kg were fed on Dec 13th during the second test run. The high residual humidity of 25% implied that no water had to be added to allow for complete conversion of organic materials including polymers into synthetic gas.

The total time required to process each batch was 1.5-2 hours, and the total combined processing time for 312kg of gillnet material would have been on the order of 5-6 hours including system setup, pre-heating and preparation. Cooling of the solid residuals requires the reactor to remain unused for 24 hours before solid residue can be removed. Hence, a total of 2 days processing time would be required to process between several 100 kg and 5 tonnes of derelict fishing gear at full capacity.

5.2.3 Results

Energy consumption

During the test runs, the typical power requirement of the reactor was on the order of 100kW, and the run time was approximately 3 hours including a 1-1.5-hour pre-heating interval. The total energy requirement hence was on the order of 300kWh per run or 600kWh for the full 312kg to be processed in 2 different runs. In a single run, this would reduce to approximately 500kWh including a single pre-heating run.

In the unrealistic case that the full energy return of 30,000 kJ/kg in 312 kg, or 2600 kWh, could be generated in the form of synthetic gas, there would be sufficient energy within the material to provide the running cost of the reactor and a surplus of about 80% of energy output in the form of synthetic gas. This could lead to the premature conclusion that the energy in gillnet-dominated DFG might offset both the hydrothermal conversion as well as the pre-processing steps. However, the ash sample was only 30% of the total sample by mass, consistent with EXOY finding that only 21% of the input material was converted into energy gas. Hence it must be assumed that only 20-30% of the total weight contains this calorific value, which would reduce the maximum output to 520-780kWh, just sufficient to mitigate the energy use of the thermal gasification of this amount of input material. In addition, total conversion of calorific value in the raw material into synthetic gas is not feasible and the fraction of energy entering the syngas is currently unknown. Fuelling a turbine with syngas for energy generation implies additional losses through the energy efficiency provided by the turbine. The true output would have to be evaluated in a test facility that has a turbine attached. In the EXOY test facility, this is not yet the case, although immediate energy return into the system is planned for the near future.

As a final preliminary result, it can be stated that the gillnets retrieved from the sea provide sufficiently high calorific value to just mitigate the energy costs of high-temperature thermal processing. Further tests with realistic energy use would be required to confirm this preliminary interpretation.

Input mass	Gas output m3	CO %	CO2 %	CH4 %	H2 %	total fraction	Solid Residue
138 kg		24.1	11.1	8.3	47.1	90.6	108.5 kg
174 kg		21.8	6.6	5.0	40.2	73.6	42.5 kg
312 kg							151 kg

Table 5.1: Gas and solid output of the hydrothermal processing test runs.

Conversion into synthetic gas

During the first testrun, 21% or 29kg of the 138kg of input material were directly converted into synthetic gas. The gas composition is given in Table 5.1. During the second test run the conversion fraction was not provided, but as the input material was identical to the first sample, the same conversion rate implies 36.5kg of polymer-organic material was presumably converted into synthetic gas.

The dominant components of the syngas are represented by CO, CO_2, CH_4 and H_2. In the case of direct burning of these fractions, the CO and CH_4 (methane) components can be used to generate energy, while they would contribute to greenhouse gas emissions if emitted without consumption. The oxygen in air leads to conversion of CO to CO_2 and CH_4 to CO_2 and H_2O. Likewise, H_2 is converted to H_2O by burning in air. Carbon dioxide and water are then the final emission components. While CO_2 contributes to greenhouse gas emissions as expected upon energy generation from carbon-based raw materials, there are no additional toxic or otherwise hazardous emissions generated in the high-temperature thermal gasification process as all polymers and other organic molecules are fully disintegrated.

A special feature of the synthetic gas produced from organic waste during steam reforming is the high hydrogen content. The conversion of gillnets let to a hydrogen content of 40-47% by volume. This is higher by more than one order of magnitude when compared to natural energy gas. In the case of low residual chemical contamination, the synthesised gas might provide fuel for hydrogen burning cells as the hydrogen extraction rate could be substantially more efficient than from natural gas, where methane comprises the predominant source of the extracted H_2. The hydrogen extraction from synthetic gas also needs to be compared to hydrogen generation through electrolysis, which however is an energy-intensive process.

In summary, the synthetic gas can be directly fed into the natural gas system for energy generation, but the most efficient use might be the extraction of hydrogen e.g. for hydrogen burning cells.

Solid material output

A total of 151 kg (48%) of solid residue was expelled from 312 kg of input material during the evaporation process. The solid residue consisted of two fractions: solid fragments dominated by molten and resolidified lead and a fine black powder that contained magnetic dust as well as fine-grained lead residue. While larger iron parts were extracted after shredding in the magnetic metal separator, lead is non-magnetic and hence could not be extracted in this process. As density separation of several tonnes of material was not feasible given the existing facilities, the high-temperature hydrothermal process provides an affordable method to separate lead and other metal residue as well as sediments from the organic polymers. The lead can be fed into metal recycling facilities rather than having to be dumped as hazardous waste. Hence steam reforming /UHTH or similar extraction methods provide the additional benefit for the environment that the lead can be re-used and does not need to be discarded in sub-terrestrial toxic waste mines or hazardous waste landfills, which would imply re-introduction into the terrestrial environment.

Fig. 5.4: Solid residue: magnetic dust with iron content (left) and recondensed lead fragments (right). © EXOY

The black dust contained 42% of fine-grained lead according to a preliminary analysis of EXOY, in addition to other inorganic residue such as sediments and other metals. As large lead fragments were already removed, 42% of lead in the fine solid residue imply a lead contamination of at least 20% by weight in the input material. The average density of 2.1 t/m^3 implies a large metal content. The fact that the dust is magnetic suggests that it contains iron residue in addition to lead, which is non-magnetic. Steel and other iron fragments were therefore not 100% extracted by the magnetic metal separator following the shredding process at Vecoplan AG (see Sec. 2).

EXOY suggests that "gravimetric vibrational or centrifugal separation methods" might be used to extract metal residue from "clean solid residue disposable in landfill". The extracted metal could then be recovered and recycled.

In addition to the fact that lead is hazardous waste, the large content of metals by weight has a negative impact on the energy efficiency of the thermal processing. The increased material weight and density consumes energy in the feed auger and in all transport processes. The gas output is low as compared to total material input. EXOY suggests that the high lead content might prohibit the regeneration of the required energy throughput of the reactor. They conclude that this form of material does not deliver energy output, but consumes more energy than is generated. A removal of lead beforehand would change the mass efficiency of the material substantially, by a factor of 3-5 as the input material only contained 20-30% organic material by mass.

5.2.4 Conclusions from high-temperature thermal processing

In summary, extensive pre-sorting of net material is not required to process material in the hydrothermal reactor. Extraction of large metal pieces and shredding to 20-40mm fibre lengths would be sufficient to prepare DFG for hydrothermal processing. However, removal of lead and other metal and sediment residue prior to hydrothermal processing would result in efficient energy generation, while non-removal leads to higher or at most equal energy consumption as is generated in the output synthetic gas.

On the other hand, hydrothermal conversion of derelict fishing nets and especially gillnets allows to extract the residual lead and metal content for recycling where a complete manual extraction is too costly, time-consuming or technically not feasible, such that depositing derelict fishing gear as hazardous waste can be avoided. This alone renders hydrothermal processing a valuable technique to recycle derelict fishing gear and possibly other sources of marine plastic waste.

5.3 Pyrolysis-techniques

Pyrolysis allows the anoxic conversion of organic carbon compounds into gas, liquid condensate and solid ash and coke. The temperature, heating and cooling curves, and duration determine the relative fractions of solid, liquid and gaseous components. As in the case of steam reforming, residual metals and especially the lead contamination inherent to lost gillnets is extracted in the solid ash residue, which can be further processed for metal recycling. Because of the higher coke content, post-processing will be more laborious than in the case of steam reforming.

Pyrolysis with temperatures of 400-800°C provides – in comparison to steam reforming – a low-temperature processing technique. The advantages lie in the lower energy input required to run the reactor and the potential output of converted organic materials in the form of a condensate. In principle, pyrolysis condensate can directly be used to feed boat engines or other fuel-based energy generators. The disadvantage in the lower temperature regime is that not all molecules are fully converted into unharmful gas content. The lower temperatures and pressures in the pyrolysis oven compared to steam reforming, and the absence of humidity providing hydrogene and oxygene as binding atoms, cause the carbon of disintegrated polymers to fall out as coke instead of CH_4 and CO_2 gas emissions. DFG is a particularly difficult mix of polymers because it is composed predominantly of PA and PET. Currently, some industrially used pyrolysis reactors work with polymer mixes dominated by polyolefins with a maximum of 10% PET in the input material because PET crystallises in the condensation pipes and can block the output channels (O. Riedel, P. Foth, Biofabrik, private communication). In addition, the pyrolysis depolimerisation process can lead to residual toxic emissions, especially when the input material contains PA, which requires a post-combustion or filtering stage. PA is currently not accepted in the Biofabrik's pyrolysis system to avoid emissions with a high toxicity level. The hydrocyanic acid generated in the process has to be neutralised in a filtering stage e.g. with sodium hydroxide (caustic soda) when the output gas is not immediately burned, adding technical complexity to the system.

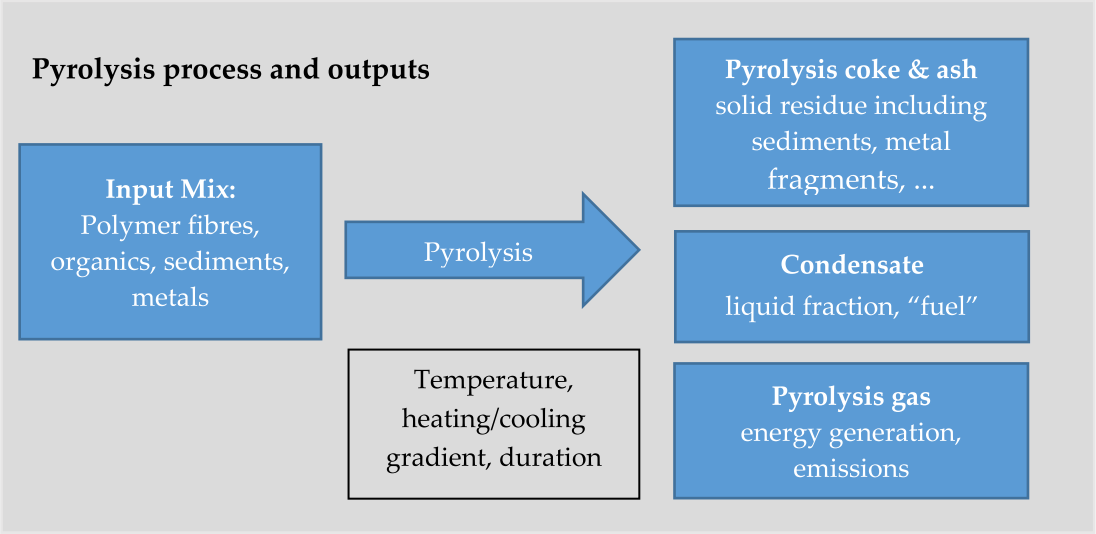


Fig. 5.5: Schematic illustration of the pyrolysis process and outputs.

5.3.1 Experiment setup

Laboratory-scale experiments were carried out at the Technical University of Aachen, Germany (RWTH) in the working group of Prof. Dr. Quicker. Experiments were carried out by Johann Hee under supervision of Thomas Horst, and Fig.s shown below are extracted from the final report provided by these authors. The pyrolysis oven provided a temperature range from 400 to 750°C, and trials were run with 500, 600, and 700°C. For direct comparison with the steam reforming trials, the same gillnet-dominated input material retrieved in Ahlbeck was used. Lead fragments of 10mm length with a diameter of 2mm were notably present in the samples. Prior to the pyrolysis trials, the material was analysed following standard waste management procedures. Because of the inhomogeneity of the samples, 8 subsamples of 2 liters each were mixed to 4 samples of 4 liters, which were reduced to 2 homogenised 4 liter samples with masses of 1.29kg and 1.38kg, respectively. From these samples, 500g were used for the 500°C pyrolysis trial and 800g were used for each of the 600 and 700°C trials.

Fig. 5.6: Gillnet-dominated input material (left) and sink line fragments composed of mantled lead (right). © TEER | RWTH Thomas Horst, Johann Hee

Heating value and chemical pre-analysis

A heating value analysis was conducted on the first of the two samples. To allow for fine-grinding to a grain size of <0.75mm, metal fragments were manually removed and sediments extracted with a sieve. The remaining fibre fraction contained fine-grained residual sediments and could be fine-ground to the required 0.75mm grain size. Masses of metal, mineral, and fibre fractions were measured to recalculate the derived heating values to the absolute calorific energy content of the sample. In addition to the heating values, the residual humidity, the ash content, volatile compounds, carbon, hydrogen, nitrogen, sulfur and chlorine content were also determined. The results from multiple testing are shown with relative standard deviations in Figs. 5.7 and 5.8.

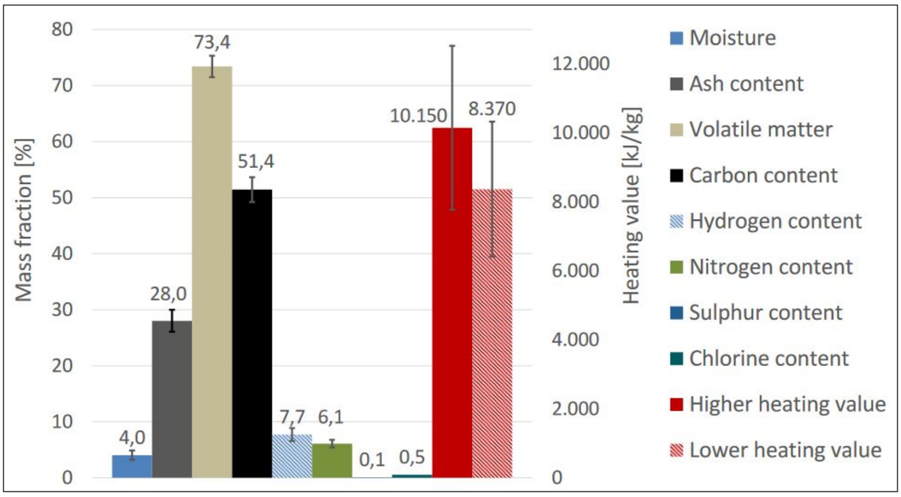


Fig. 5.7: Results of pre-analysis of extracted, fine-ground fibres. Heating values are higher than for the complete samples because metal and sediments had been removed. © TEER | RWTH Thomas Horst, Johann Hee

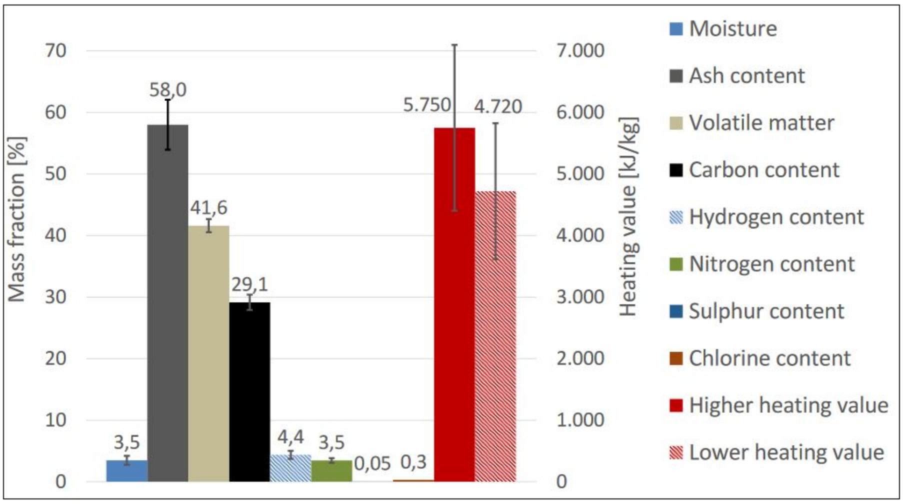


Fig. 5.8: Results of pre-analysis of extracted, fine-ground fibres. Heating values and material fractions are recalculated for the complete input sample from the mass balance of the metal, sediment and fibre fractions extracted prior to analysis. © TEER | RWTH Thomas Horst, Johann Hee

The total mass fraction does not add up to 100% because of the highly inhomogeneous material, which could not be fully processed in the analysis procedures. The inhomogeneity of the fibre mix also implies that individual samples for each analysis deviate significantly from each other. The carbon content originates from organic material, including polymers, and the higher the carbon content the higher the expected calorific value. Residual ash contains sediments and metals not available for energy generation. The recalculation from extracted fibre material to the complete mix of fibres, sediments and metal fragments leads to a reduction in heating value by about a factor of two in both upper and lower heating value. This is expected given the high metal and sediment mass fraction in the raw input material, which is also reflected in an increase in ash content and a decrease in carbon content in the recalculated components.

Pyrolysis experiments

The setup of the experiment in the TEER lab at RWTH Aachen is shown in Fig. 5.9. During pyrolysis, the oven was flushed with nitrogene to maintain the anoxic atmosphere. After reaching maximum temperature, the pyrolysis gas flows through two consecutive cooling flasks (-20°C) to obtain the condensate. The volume of the residual, not condensable gas is measured and the gas fraction is burned to avoid toxic emissions.

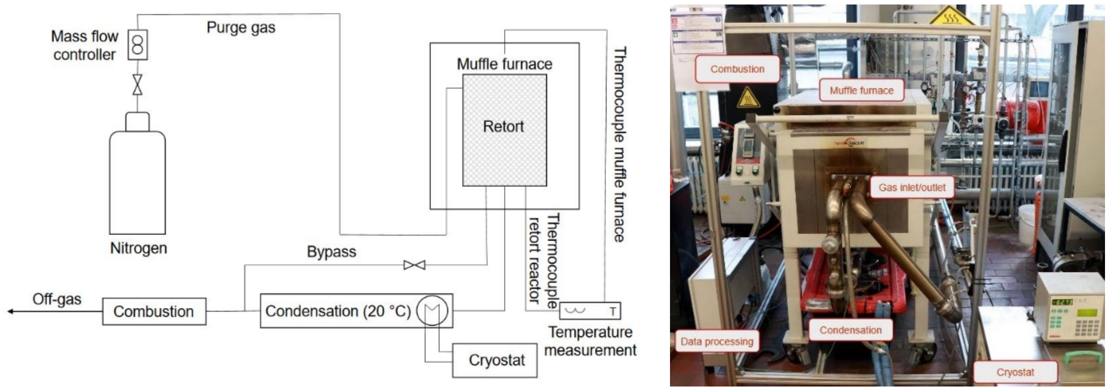


Fig. 5.9: Schematic and photographic illustration of the experiment setup at TEER at the RWTH Aachen. © TEER | RWTH Thomas Horst, Johann Hee

Heating the samples was conducted in 2 steps. Volatile components were degased at 250°C for 30 minutes to avoid pressure built-up and decrease explosion risk before heating to the maximum reactor temperature of 500, 600 or 700°C. The duration at maximum temperature was set to 60min in all trials, after which test trials showed almost complete conversion of the input material. The same total processing time was achieved by a more rapid heating curve in the case of the higher temperatures.

5.3.2 Results

During the first trial at 500°C, the pyrolysis gas stream increased noticeably at 494°C and gas escaped from the system, such that the gas had to be sucked out. The gas mass fraction was therefore determined as the difference from the input material mass and the condensate and solid residue outputs. The results of all 3 trials are shown in Fig. 5.10. In all 3 trials, the outputs are approximately split into two thirds solid residue and one third gas emission by mass. The solid residue had a metal content of 39-44% in all three trials. Spheres and linear fragments were both observed (Fig. 5.10), and copper was visible in addition to lead and presumable iron/steel fragments. The organic coke residue decreased from 12% to 3% with a temperature increase from 500 to 700°C. The low mass fraction of the organic residue at 500°C suggests that lower temperatures are sufficient for DFG processing.

The hydrogene content of the pyrolysis condensate was 10-11% in all trials. The lower (net) heating value of the condensate ranged from 29,000 to 33,500 kJ/kg and showed a systematic decrease with increasing processing temperature as a consequence of more complete polymer disintegration into the gas phase. While this would argue for processing at 500°C, the condensate consistency was a thick "wax" or highly viscous "crude oil" at lower temperatures that could only be used as fuel with a prior heating stage to liquefy the condensate. Engines capable of processing crude oil would likely be able to cope with these types of condensates, but more sensitive machines running, e.g., on diesel fuel might not be able to process the viscous pyrolysis condensates. Only the 700°C trial resulted in a pourable condensate with low viscosity and a total mass fraction of 5% of the input material. Despite the higher energy required for heating, higher-temperature pyrolysis was the only process capable to generate a condensate that could, in principle, be used as engine fuel without a prior heating stage. If fuel generation is one major aspect of pyrolysis processing of DFG or other forms of marine litter, such high temperatures would need to be recommended as a result of the DFG trials at TEER|RWTH Aachen. However, a complete chemical analysis of pyrolysis condensates would be required to conclude whether these condensates fulfill the DIN normes for boat engine fuels. With highly diverse input materials such as DFG or other mixed marine litter, contaminants are likely to decrease the condesante quality (e.g., sulfurs or heavy metals such as a high lead content). This would impede their use as engine fuels for both technical and environmental reasons.

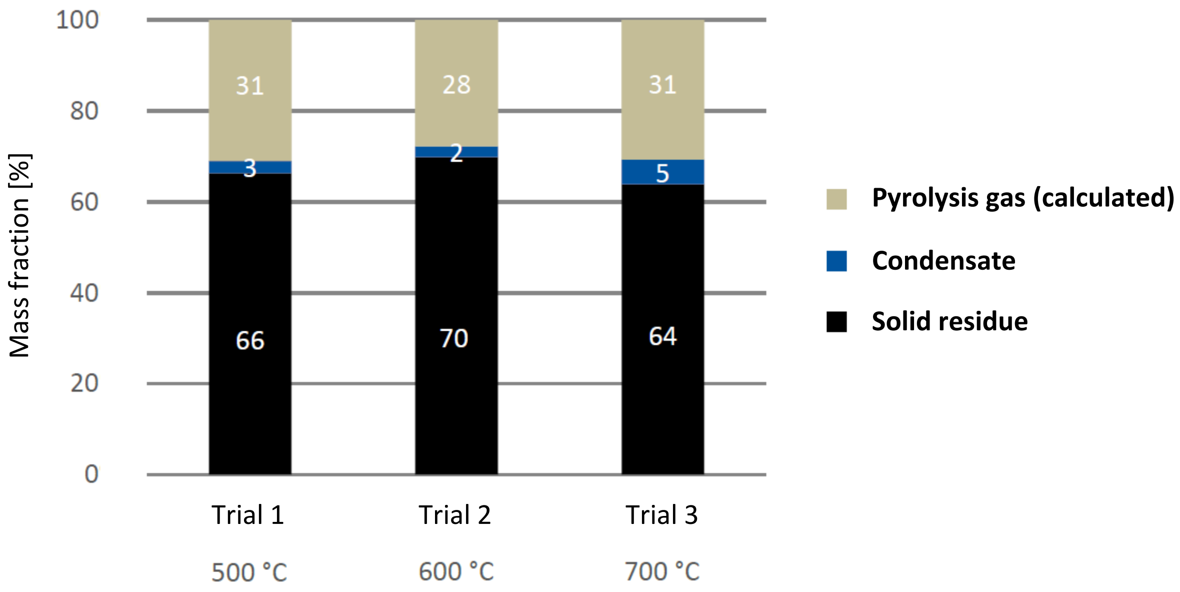


Fig. 5.10: Solid, liquid (condensate), and gaseous output mass fractions of the 3 pyrolysis trials. © TEER | RWTH Thomas Horst, Johann Hee

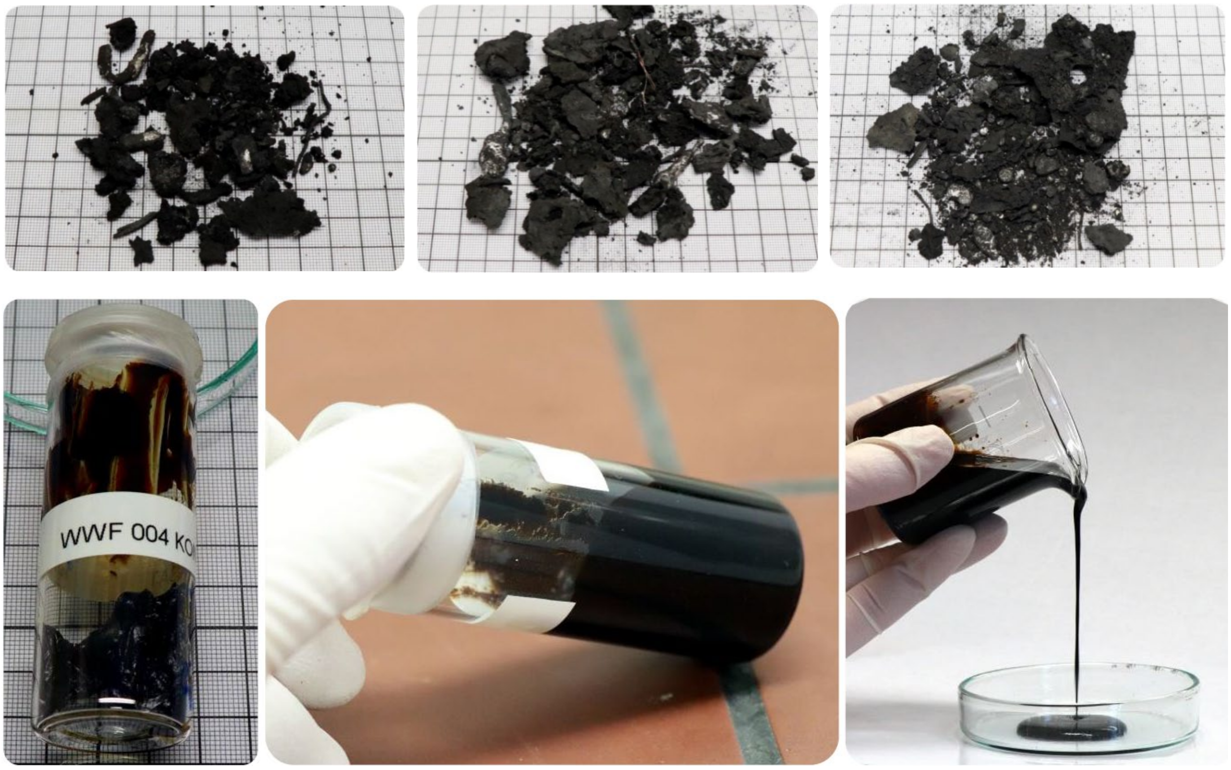


Fig. 5.11: Solid residue (“coke”, top) and condensate (bottom) for the 500, 600, and 700°C pyrolysis trials from left to right, respectively. © TEER | RWTH Thomas Horst, Johann Hee

5.3.3 Summary of low-temperature thermal processing

Pyrolysis is discussed, and in other countries already used for instance on US Navy ships, as a method to process household and collected marine litter at sea to provide engine fuel for continuous ship operations. Our trials show that the conversion of retrieved fishing gear, in particular gillnets, yields only a very low condensate mass output fraction of a few percent. The solid residue has to be processed further to extract the metal content for recycling. For ship-based pyrolysis systems, the large fraction of 60-70% of solid residue by weight still needs to be stored and brought to land for further processing. The laboratory-scale pyrolysis trials therefore suggest the low-temperature processing to be less suited to process retrieved fishing gear than higher-temperature alternatives.

With a condensate mass fraction of a few percent and a pyrolysis gas mass fraction of 30%, to achieve an economically profitable use of DFG in the form of fuel or gas for energy generation is unlikely. In the presence of PET or PA as expected in DFG and mixed marine plastics, the pyrolysis gas has to be filtered or post-combusted to remove toxic emissions such as hydrocyanic acid, leading to a more complex system than higher-temperature alternatives. Post-combustion of the pyrolysis gas might be preferable as it would provide a heating source. The extraction of metals for recycling is highly recommended, and in the absence of higher-temperature facilities, pyrolysis provides a technique for scrap metal re-use. Hence pyrolysis can be used to avoid depositing of DFG as hazardous waste in landfills because of its high lead content.

5.3.4 Summary of thermal processing trials

Gillnet-dominated DFG samples could be processed without technical problems both in low and high-temperature reactors. High-temperature processing (“steam reforming”) proved more efficient because of the relatively pure lead and metal solid residue that can directly be recycled. The process mitigates the need for toxic lead-contaminated DFG to be deposited in hazardous waste facilities. The high temperatures also ensure the complete conversion of organic compounds, such that toxic emissions (eg. hydrocyanic acid from PA) are avoided. The resulting hydrogene-rich gas might be used to generate hydrogene for fuel cells or to drive turbines for energy generation. In the case that a substantial waste stream can be generated, e.g. by combining DFG with other forms of marine litter in littered environments, the metal and energy outputs might render steam reforming economically profitable. Steam reforming is most promising for the processing of highly mixed and contaminated DFG which cannot be sorted for material re-use.

In the discussion around marine litter mitigation at sea, the pyrolysis condensate is advertised as fuel that could support operating the continuous collection of litter. Our pyrolysis trials result only in 2-5% of the mass fraction in the form of liquid condensate from DFG materials.[4] While this would need further testing with collected marine plastic litter, such a low fraction of condensate renders pyrolysis a highly inefficient process. In addition, the useability of mixed plastic litter condensates as engine fuel might be limited both from the technical and environmental perspective by hazardous contaminants. Storage of 60-70% of the mass fraction as solid residue would also be technically challenging at sea. For retrieved fishing gear, pyrolysis is inefficient in comparison to steam reforming. The metal content is more difficult to extract due to the larger coke residue. This requires further processing while providing a less efficient conversion of organic compounds (polymers) into energy gas. While the heating of the reactor requires less energy because of the lower temperatures, the larger post-processing efforts to extract the metals for recycling need to be factored into the efficiency calculation. Because post-processing was not tested on these samples, and the sample mass was small, a final comparison of energy efficiency cannot be provided.

6. DFG material recycling

6.1 Introduction to recycling options

From the results in the previous sections and especially from the chemical analysis it is clear that DFG is not an easy material to re-introduce into the circular plastic economy. For end-of-life fishing gear, several projects worldwide are running successful recycling trials that already led to the production of consumer goods. The Danish company Plastix Global collects end-of-life fishing gear from harbours in Northern Europe and Canada to produce recyclates in the form of standard pellets with 95% of recycled polymer content (http://plastixglobal.com/). The properties of these PE and PP granulates were compared to the physical properties of DFG samples in Sec. 4. The Chilean and Californian company Bureo uses end-of-life fishing nets from Chilean and US fishing harbours to produce skate boards, sunglasses and investigates into other beach items (https://bureo.co/). The Italian-Slovenian company Aquafil uses end-of-life fishing gear from Norway with some contribution of retrieved fishing gear, especially fish traps, from Norwegian waters mixed with end-of-life carpets to produce polyamide “econyl” yarn (http://www.econyl.com). The shoe producer Adidas has used a small amount of fishing gear in the top layer of their “fishing net” limited edition runners and is considering a second, more extended edition. There is clearly an interest in recyclates generated from discarded fishing gear in the recycling and outdoor market.

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[4] Only in the case of pure, pre-selected polyolefins can a high condensate return of 1 litre per kilogramme of input PE/PP be achieved (Oliver Riedel, biofabrik, private communication). Whether such a pre-sorting is possible at sea and captures a large fraction of the marine plastics potentially retrieved is currently unclear.

The problem with DFG in contrast to end-of-life fishing gear is the high potential contamination with toxic substances. Both the lead and chlorine content would currently not permit the affected materials to be converted into consumer goods. When discarding end-of-life gillnets, fishermen cut off sink lines for re-use in the new netting. In lost nets, these hazardous materials are still attached. Heavy entanglement during exposure in the sea prohibits cutting out the lead lines or fragments, as discussed above. At the same time, plastics with a long residence time in the sea can absorb toxic substances from the surrounding seawater. This is of particular concern for DFG, as retrieved DFG in German waters was identified to be at least 25 to 30 years of age from the composition of the net material and the shape of the floats. It is unclear how much contamination from hazardous substances DFG can absorb during decades of residence in contaminated seawater or on affected sediments. This renders material recycling of DFG much more complex than end-of-life fishing gears.

During MARELITT Baltic, the Technical Unversity of Magdeburg-Stendal offered to conduct test trials with the aim to identify material re-use options for DFG. The working group of Prof. Gilian Gerke had already conducted similar trials for trawl netting and ropes retrieved during the fishing-for-litter project of the German NGO NABU (Gerke et al. 2016). With the aim to extend the scientific results of the previous study into the regime of gillnets, Prof. Gerke and her team analysed and processed 54 kg of the Ahlbeck gillnet material to identify gillnet recycling options and limitations. The sections below summarise the findings from these trials.

All images, spectra and results displayed below are provided by the Technical University of Magdeburg-Stendal through Prof. Dr. Gilian Gerke and Dr. Gunter Weißbach (Weißbach & Gerke 2018).

6.2 Materials and methods

The pre-shredded, density-separated and washed samples of the Ahlbeck gillnet material as delivered by Vecoplan AG (see Sec. 2) were further grinded in a laboratory cutting mill. In order to avoid overheating, 4 mill runs were conducted consecutively using 10mm, 8mm, 4mm and 1mm sieve sizes. This led to output net fragments of about 1mm grain size after the final grinding run. For microscopic structure analysis, an additional sample with 0.08mm very fine grain size was generated using a centrifugal mill.

ATR-FTIR (Attenuated Total Reflection-Fourier Transform Infrared) spectroscopy with a Bruker-Vector 22 system and spectral library was used for material identification. Residual humidity was estimated through weight loss in the drying oven at 105°C (DIN EN ISO 15934:2012-11). The residual humidity of 1.9% was only used to determine the anorganic content with respect to the dry weight. Anorganic residues in the form of ashes were determined from unwashed dry samples of ~20mm grain size with at least 3 sampling trials each at an ashing temperature of

550°C (DIN EN ISO 15935:2012-11). Samples were left in the drying oven until no further weight loss was observed.

Melting points were derived using DSC analysis (differential scanning calorimetry), which was also used to confirm the major polymer content. X-ray fluorescent spectroscopy (XRF) was applied to determine residual contamination with metals. The focus of the XRF analysis was on lead because of the known presence of lead sink lines in the input material.

Due to the origin of DFG from the sea, special emphasis was placed on the determination of residual sediment content. A 1.5kg sample of the unwashed, shredded (20mm grain size) and pre-dried gillnet material was placed in a standard washing bag with mesh width < 0.5mm and washed in a household washing machine at 30°C for 1.5 hours. The washed material was dried in a drying chamber at 50°C until no further weight loss was observed. The measured weight loss between the dried pre-washing material and the dried material after washing was assumed to be the residual fine-grained sediment content.

Densities of individual polymer fractions were measured with a pyknometer following DIN EN ISO 1183-3. The fractions for density measurements were extracted manually from the raw material sample that had not been previously processed at Vecoplan AG.

The grain size distribution was measured from dried fibres with 1mm grain size in a sieve tower with consecutive sieve mesh widths of 1.0, 0.5 and 0.25, 0.1, 0.08mm following DIN 66165.

Density separation trials were carried out in a 100-litre acrylic tube with tap water and enriched saline solution (compare to density separation methodology in Sec. 2). Five samples of 1kg each of the pre-washed fibres shredded to 20mm grain size were used as input materials. After a separation time of 2 hours, the floating fraction was retrieved with a sieve, while the sinking fraction was obtained with the residual water after the surface fraction had been extracted. A second density separation stage in enriched saline solution was carried out with one 100g sample of both the floating and sinking fractions of the tap water trials. The fractions from the saline swim-sink separation were rinsed with clean tap water and filtered after extraction. All samples were dried in the drying oven at 50°C until weights were constant.

In addition to density separation, chemical separation of the PP fraction was also attempted through dissolution in xylol at elevated temperatures. This process would result in a purer PA6 fraction after PP was chemically removed from the material mix. Results were not sufficiently promising such that this extraction methodology was not pursued further.

The gillnet-dominated material was hot-pressed into plates to test homogenisation and the behaviour of the compressed polymer matrix.

6.3 Analysis results

Several characteristic materials were analysed at the TU of Magdeburg-Stendal with regard to their recycling potential. Six typical material fractions contained in gillnets were manually extracted from the raw material not previously shredded or washed.

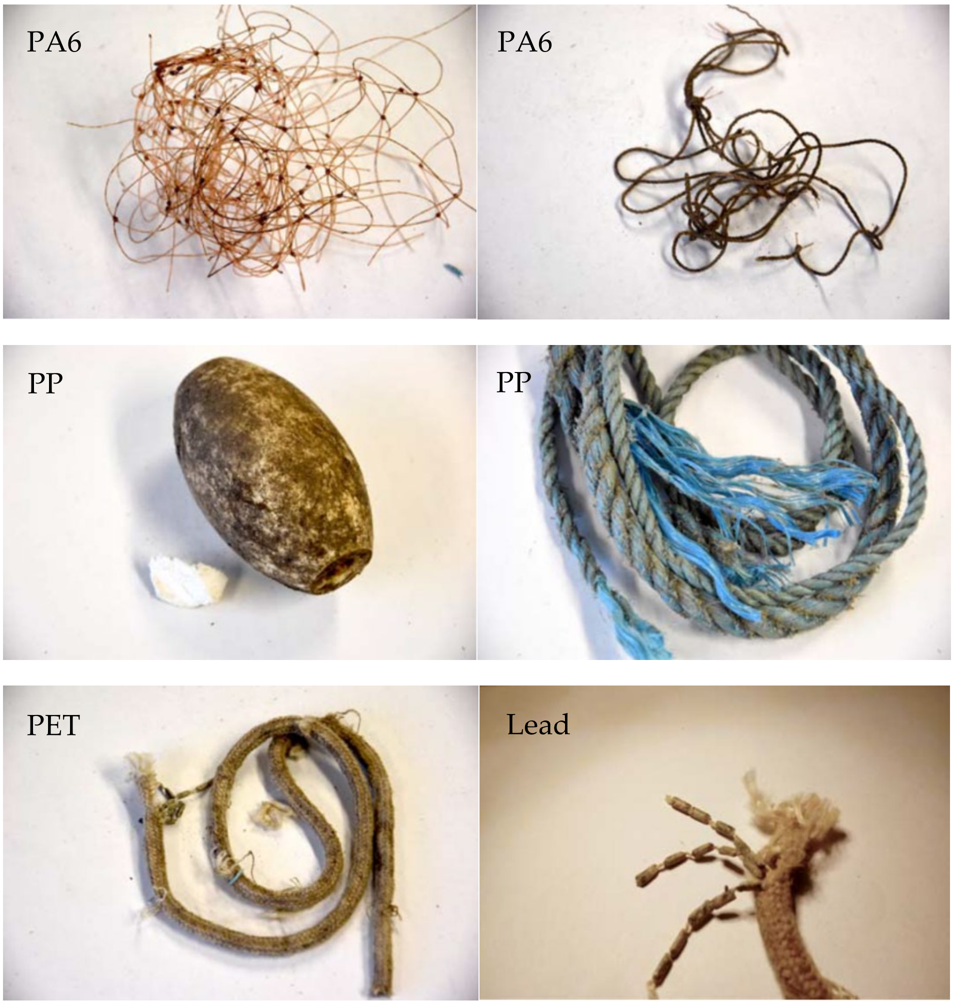


Fig. 6.1: Sample materials from Ahlbeck gillnets. a) Monofilament line, b) twisted line, c) float, d) rope or swim line, e) sink line sheathing, f) lead fragments embedded in sink line. © Gerke & Weißbach 2018

Samples of the manually extracted individual material fractions are shown in Fig. 6.1. The diversity of the material including monofilament and woven netting as well as lead lines in polymer sheathing, ropes and floats is evident in the images. These fractions were used to identify dominant polymer content and material properties.

6.3.1 Polymer identification from ATR-FTIR spectrocopy and DSC

The dominant polymer contribution in monofilament fragments and woven netting was confirmed to be the polyamide PA6. Floats and blue rope fibres were found to be composed of PP. The sheathing of the lead line was woven from PET.

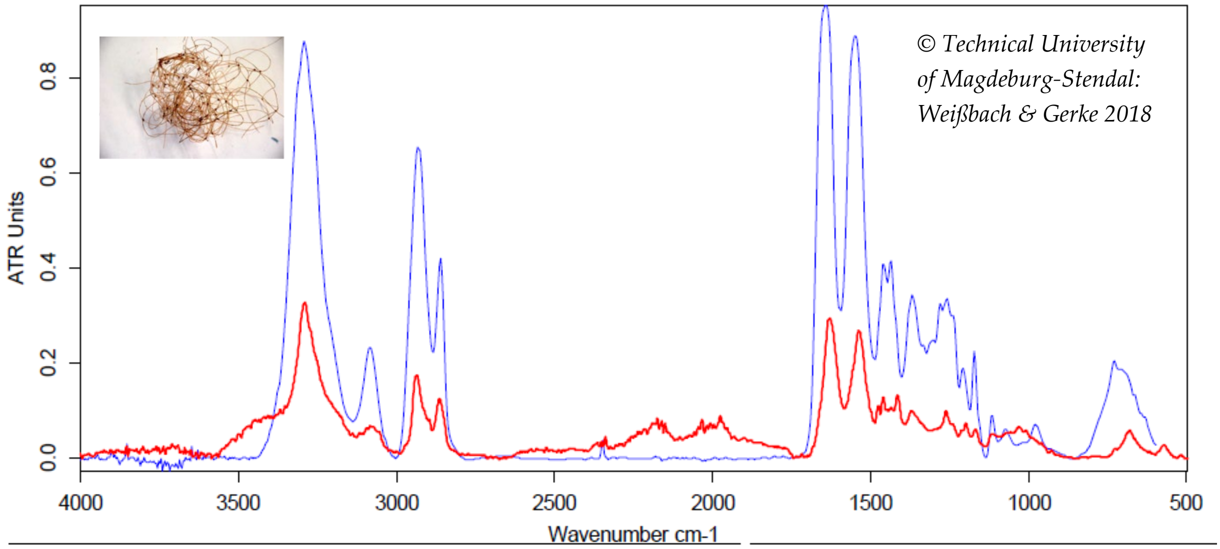


Fig. 6.2: FTIR spectra of Ahlbeck monofilament gillnets (red) in comparison to a PA6 template spectrum (blue, © Bruker spectroscopic library).

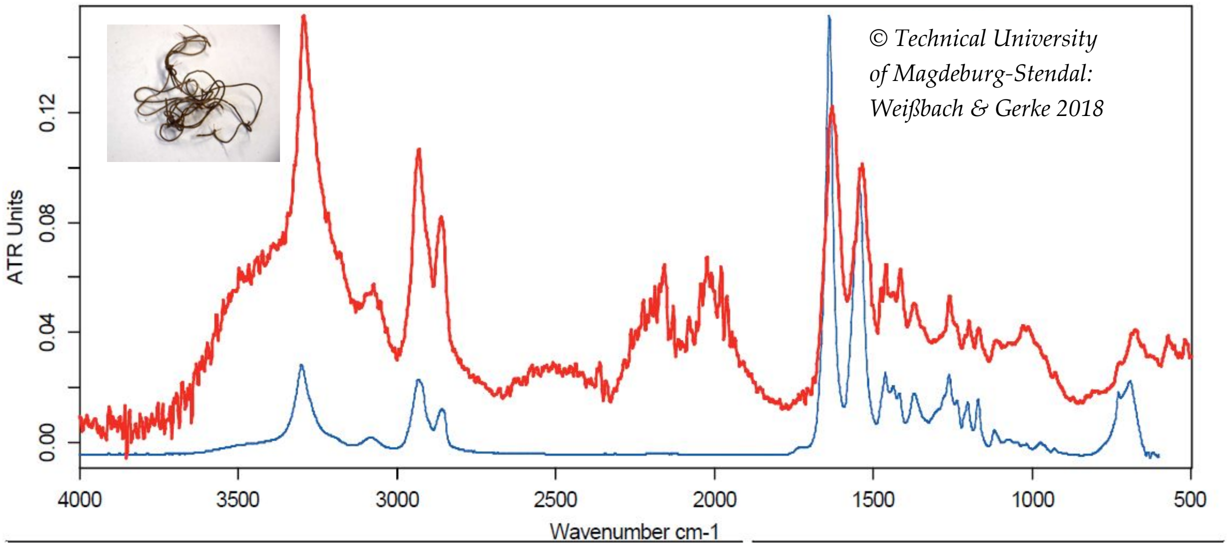


Fig. 6.3: FTIR spectra of Ahlbeck twisted line netting (red) in comparison to a PA6 template spectrum (blue, © Bruker spectroscopic library).

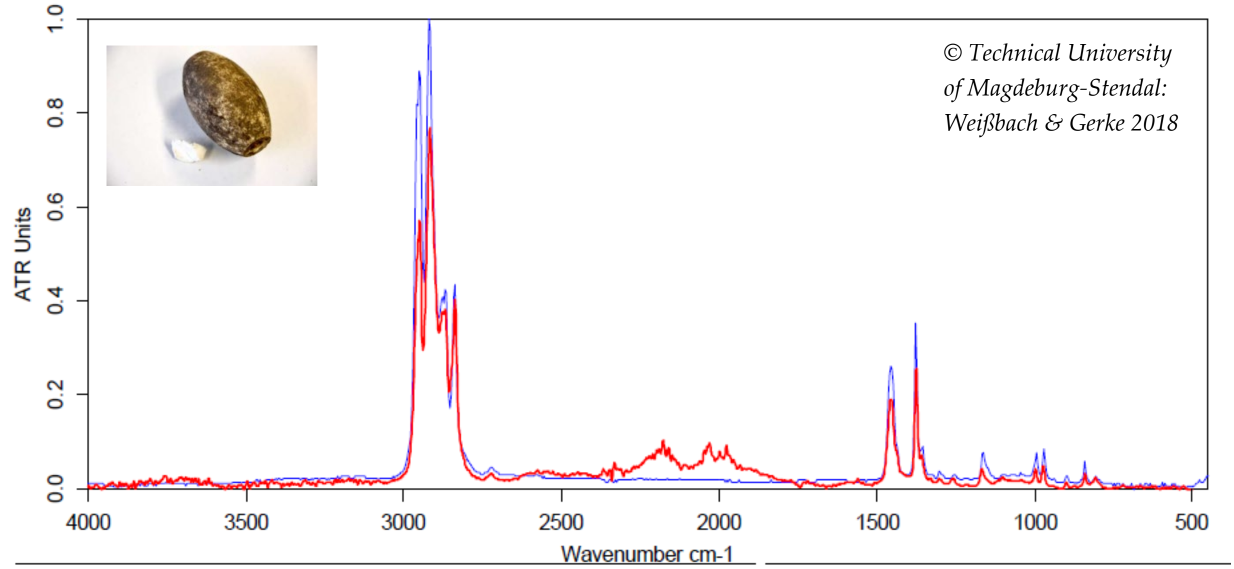


Fig. 6.4: FTIR spectra of floats from the Ahlbeck gillnet sample (red) in comparison to a PP template spectrum (blue, © Sadtler spectroscopic library).

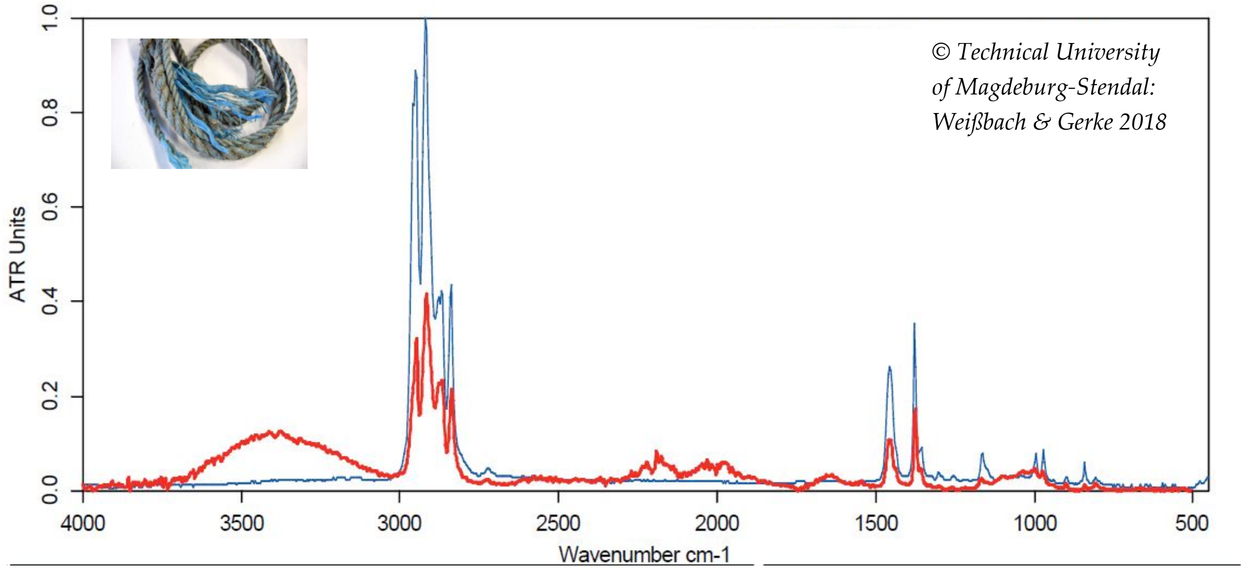
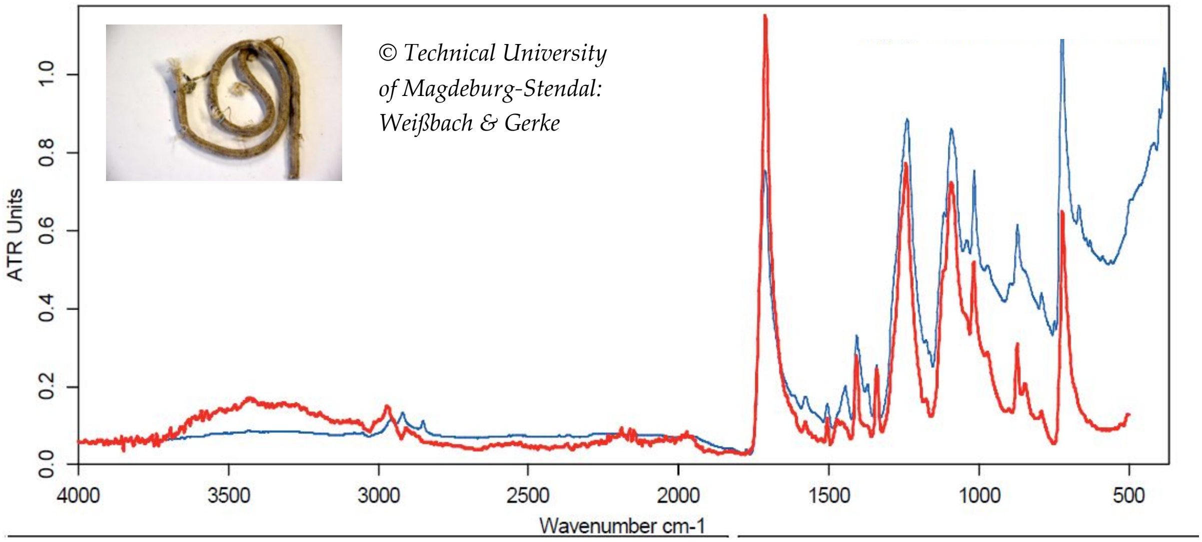


Fig. 6.5: FTIR spectra of blue rope or floatline extracted from the Ahlbeck gillnet sample (red) in comparison to a PP template spectrum (blue, © Sadtler spectroscopic library).



© Technical University of Magdeburg-Stendal: Weißbach & Gerke

Fig. 6.6: FTIR spectra of sink line sheathing extracted from the Ahlbeck gillnet sample (red) in comparison to a PET template spectrum (blue, © Bruker spectroscopic library).

Similar results are obtained from thermal DSC analysis of one fibre sample from the mixed, shredded and pre-washed gillnet material. Four thermal peaks are observed at 136, 173, 228 and 258°C, in close correspondence to the melting points of PP (160-184°C for partially crystallised PP), PA6 (220 °C) and PET (250-260°C, source: wikipedia). The lowest melting point corresponds to PE (130-145°C), which is known to be present in the Ahlbeck samples from material analysis (see Sec. 4). The differential thermal analysis suggests that the three polymer types originating from monofilament and twisted netting, floats, and sinkline sheathing are well-mixed in the final, processed fibre sample. This mixing complicates the material separation process and impedes material recycling in the form of regranulation. The mixed fractions once more suggest that efficient pre-sorting is crucial to exploit the material value of retrieved gillnets.

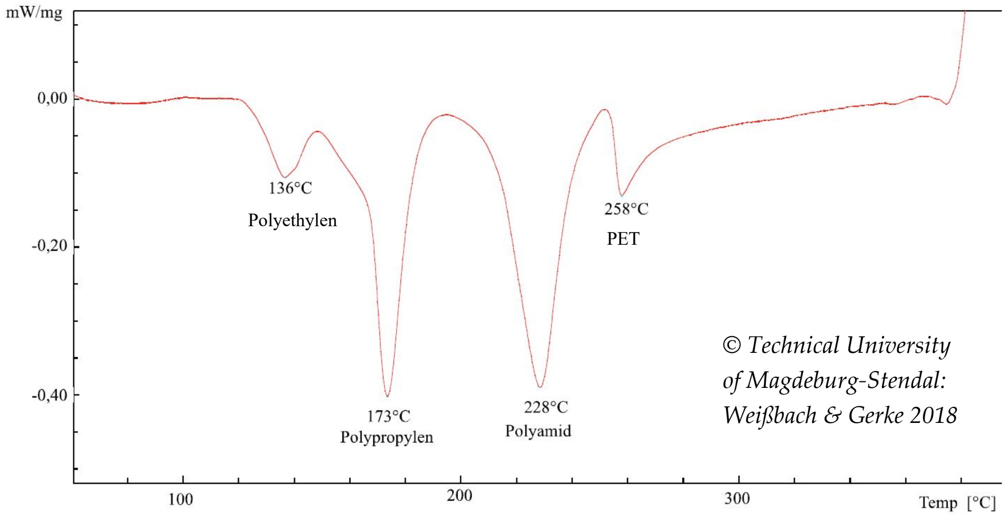


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Fig. 6.7: Differential scanning calorimetry (DSC) spectrum of one complete fibre sample drawn from the shredded, pre-washed Ahlbeck gillnet sample. The endothermal peaks correspond to the melting points of PE, PP, PA6 and PET. (© Weißbach & Gerke 2018)

6.3.2 Density determination

Material densities were determined for the manually extracted material types shown in Fig. 6.1 with known spectral polymer identification. A pyknometer was used to obtain the density after grinding a subsample of each fraction. The density of the two PA6 net fractions was found to range from 1.14 to 1.16 g/cm^3. The PP floats and the PP blue rope displayed densities as low as 0.58 and 0.56 g/cm^3, respectively. The PET sinkline sheathing had the highest polymer density of 1.37 g/cm^3. The lead fragments were confirmed to have a density of 11.64 g/cm^3. The large variety in the polymer densities of net and rope materials suggests that a sophisticated 2-stage swim-sink density separation procedure should be able to extract these three polymer fibre fractions from DFG samples. The results of the swim-sink separation trials are presented in Sec. 6.3.5.

Table 6.1: Polymer types, densities and melting points derived for each manually extracted material fraction displayed in Fig. 6.1 of the Ahlbeck gillnet sample.

Material fraction	Polymer type (FTIR)	Density [g/cm^3]	Melting point [°C]
Monofilament gillnet	Polyamide 6	1.16	220
Twisted netting	Polyamide 6	1.14	220
Float	Polypropylene	0.58	168
Sinkline sheathing	PET	1.37	260
Rope, blue	Polypropylene	0.56	170
Sinkline weight fragments	Lead	11.64	(327, not this study)

6.3.3 Confirmation of lead contamination with XRF analysis

The sink line fragments were confirmed to consist of lead using X-ray fluorescence analysis (XRF). In addition, several mixed, shredded fibre samples were analysed for lead contamination. The samples were pre-processed (washed, first pass swim-sink bath) at Vecoplan and fine-grinded at TU Magdeburg as described above. An XRF spectrum along with the microscopic image of one sample is shown as an example in Fig. 6.8. The lead fragments cannot be discerned in the microscope image, in contrast to black rubber contamination. Lead fluorescence lines were clearly detected in the X-ray spectra of all drawn samples, suggesting that lead has spread throughout the entire material batch, most likely during shredding. The softness of lead as a metal possibly facilitates abrasion and distribution onto the fibre surfaces. This implies that sink lines need to be removed prior to any further processing steps to avoid toxic contamination in recycling material fractions.

The distribution of lead throughout fibre samples during shredding is consistent with the finding of 358 ppm of lead in the Ahlbeck gillnet samples during chemical analysis (see Sec. 4). Even the pre-sorted ropes had a comparable lead content. From these ropes, all metal parts had been manually removed prior to any further shredding and processing. There were no lead lines in the original sample. However, the ropes were shredded after the Ahlbeck gillnets had been processed in the same machinery. This suggests that lead is not only highly prone to distribution within one sample, but also has a high probability of contaminating equipment and thus progresses into previously uncontaminated samples.

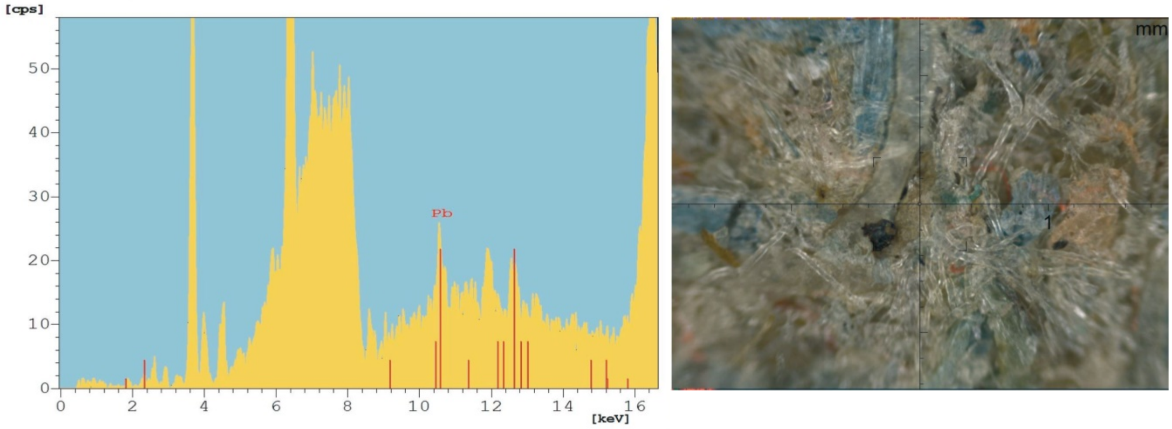

Fig. 6.8: XRF spectrum of a fine-ground Ahlbeck gillnet sample with lead fluorescence lines marked in red (left) and the microscope image of the same sample (right). The black fragment near the centre of the image is not a lead fragment, but likely black rubber. (© Weißbach & Gerke 2018)

6.3.4 Residual anorganic contamination

Anorganic residual contamination was dominated by sediments. A high-temperature ashing trial was condcuted on a test sample to determine the sediment contribution as compared to the organic matter fraction (including polymers), which is evaporated during ashing. The residual humidity of 1.9% was subtracted to determine the mass balance. A sample of the raw input material without any previous washing was used to judge the original anorganic contamination in gillnet-type DFG from the Baltic Sea, where fine-grained sediments dominate in the Southern areas.

The ashing residue suggested a residual contamination by sediments of 45% by weight. The washing in the household washing bag with 0.5mm mesh width suggested a residual weight contribution of 37% from fine-grained sediments < 0.5mm. The smaller residual contamination removed during the washing process can be explained by sediments, mussels and other materials too tightly embedded in the knots and woven lines to be removed in a single washing run. Ashing, on the other hand, will capture all residual anorganic contamination in the residual ash.

It should be noted, however, that residual sediment was also found in the 20mm pre-washed fibres as processed at Vecoplan AG (Sec. 2). Although the mass fraction of residual sediment was not measured, the swim-sink separation trials and the grinding trials revealed a non-negligible amount of fine-grained sediments in the pre-washed samples as well. While the limitations of friction washing were already discussed in Sections 2 and 3, the trials with fine-ground material suggest that material separation is facilitated for the finest grain size available.

6.3.5 Swim-sink density separation

The swim-sink density separation was found to be most efficient for the smallest grinding fraction. The original material with net fragments and large fibres up to 30mm fibre length did not separate into a high- and low-density fraction, but the sampled material stayed clumpy with embedded high-density and suspended fibre balls in the solution. After the first grinding stage with the 10mm mesh sieve, low-density fragments started to float from the higher-density fibres in tap water. Only after the final grinding with a 1mm mesh sieve did the higher-density fraction sink completely and the lower-density fraction floated with only a minor suspended particle fraction in the tap water. This result can be extrapolated to density separation in saline solution as well, where the PA fraction will start to float and be separated from the lead fragments when a fine-ground input sample is used. As a result, it can be concluded that extra grinding stages would be beneficial in an industrial DFG processing unit where density separation is incorporated. The recommedation provided by TU Magdeburg-Stendal is to fine-grind down to at least 1mm grain size in preparation for swim-sink density separation to allow the individual particles to float freely in the separation solution. The additional benefit of fine-grinding stages is that the resulting output materials would be better suited as input into extruders because of their higher pourability.

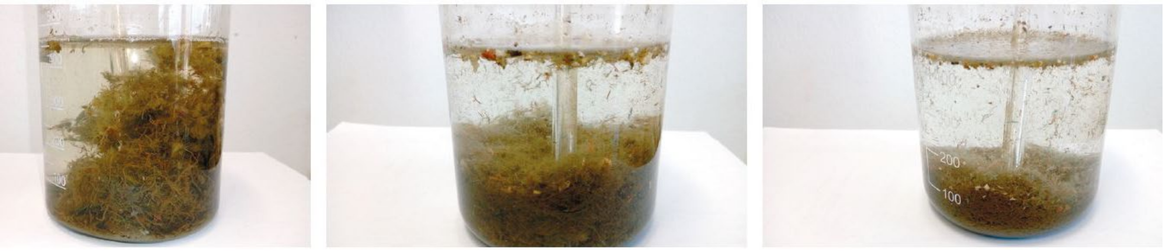

Fig. 6.9: Density separation trials with raw input material a) 20mm shredded, b) fine-ground to 1mm grain size, c) fine-ground to less than 0.5mm grain size. (© Weißbach & Gerke 2018)

The density separation trials in tap water resulted in 22% of the weight retrieved in the floating fraction and 78% of the weight found in the sinking fraction. Although some PP was still present in the sinking fraction (identified visually by the blue colour of the PP fibres), the desired enrichment of the PP fractions in the floating layer on the surface was observed. The large weight in the sinking fraction is likely a consequence of the residual sediment contamination in the pre-processed samples, in addition to the weight of the dominant PA6 fraction constituting the main gillnet material.

The density separation trial in a partially-saturated NaCl saline solution did not show any improvement of the separation into individual fractions. This is likely due to the fact that the NaCl solution could not be fully saturated and the density might not have reached the density of PA6. As a consequence, an efficient separation of the high-density polymers PA6 and PET from sediments and residual lead fragments was not feasible. The reason for the incomplete material separation was investigated through microscopic analysis.

6.4 Microscopic analysis

The aim of the fine-grinding experiments was to improve the separability of the individual polymer fractions from residual contaminants such as sediments and lead fragments as well as from each other. Grinding was applied to break up knots and loops to facilitate the cleaning process. Figs. 6.10 and 6.11 display microscopic images of the pre-washed sample before and after fine-grinding to a final grain size of 1 and 0.08mm.

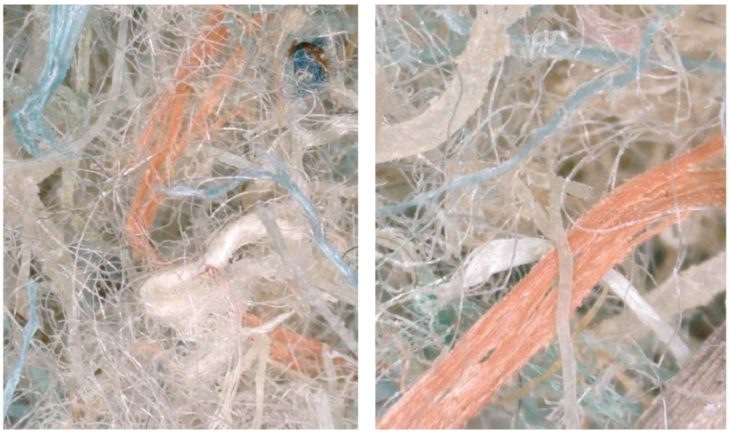

Fig. 6.10: Microscopic analysis of pre-washed input material at 20x (left) and 30x (right) magnification, showing that the material is highly twisted and contains loops and knots hindering the cleaning and polymer separation processes. (© Weißbach & Gerke 2018)

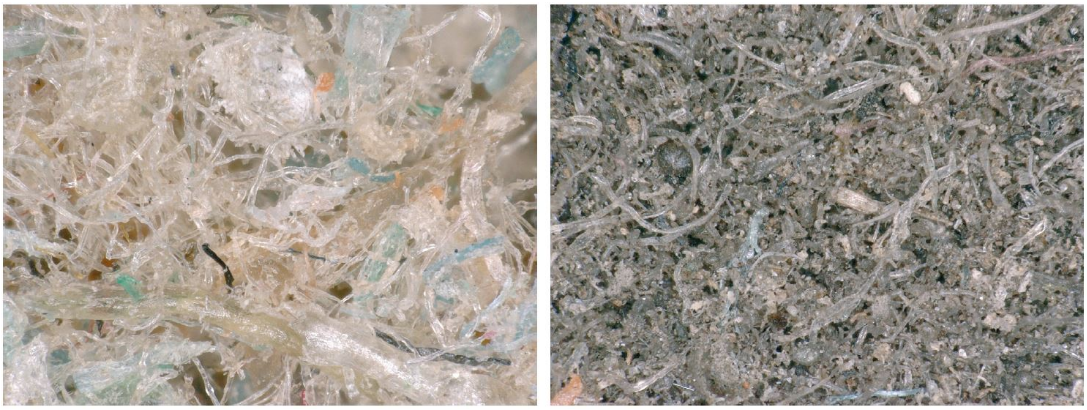

Fig. 6.11: Microscopic analysis after fine-grinding to 1mm (left) and 0.08mm (right) grain size at 100x magnification. Even after fine-grinding, loops and twists are still clearly visible in the 1mm fraction. The 0.08mm fraction is blackened because heating of the grinding mill started to coke the polymer fibres during the grinding process. (© Weißbach & Gerke 2018)

The original pre-washed input material shredded to 20mm fibre lengths shows knots, loops and fluffed up fibre compounds (Fig. 6.10), all of which will impede the cleaning process by causing fine-grained sediments and small lead or organic fragments to be trapped. Loops and twists are still clearly visible after fine-grinding the pre-washed fibres to a grain size of 1mm. The intertwined and highly diverse structure of this type of input material explains why the swim-sink separation was inefficient. Even if the pre-washed input material were used instead of the raw input material in swim-sink trials, the dense conglomerates and mixed fibre compounds indicate that a simple swim-sink density separation will remain inefficient. The complex structure and the partial fluffiness of the material prohibits fine-grained sediments and other organic matter fragments to be expelled during the density separation process. Adding centrifugation to the density separation might facilitate the breaking up of the compounds and consecutive expelling of higher-density contaminants, especially sediments and lead fragments. Industrial centrifugation cleaners were not available for these trials, but might improve the cleaning process substantially in larger-scale industrial applications.

Another problem emerged during fine-grinding. When grinding down further to 0.08mm grain sizes to facilitate swim-sink material separation, the grinding mill heated the material to the coking temperatures of the lower-density polymers. In the right panel of Fig. 6.11, this is evidenced by the dark-grey colour of the fine-ground fraction. Cooling the grinding mill during fine-grinding might help to avoid coking of the least thermally stable polymers.

6.5 Re-use trial results

With the aim to evaluate the use of gillnet-dominated DFG for consumer good production, the re-washed fibres were hot-pressed into plates of 1mm thickness. The temperature was set to 220, 230 and 240°C in three trials at a pressure of 600kN exerted for 10 minutes. The plates were allowed to cool to a temperature of 30°C in 15 minutes before removal from the press. The added washing and grinding steps were expected to lead to a more homogeneous fibre mix. Nevertheless, the compressed plates displayed a variety of impurities. In addition to being toxic, lead fragments caused inhomogeneities in the compressed polymer plates. After pressing, a previously unidentified contaminant was observed: Black rubber particles caused uneven mixing and melting that led to porous plate surfaces, as air bubbles trapped in rubber evaporated during the hot-pressing process. The black, porous “holes” (inclusions) were several millimetres wide and provided breaking points in the otherwise smooth plate surface.

Fig. 6.12: The input material for pressed plate experiments still shows severe inhomogeneities after all cleaning stages. (© Weißbach & Gerke 2018)

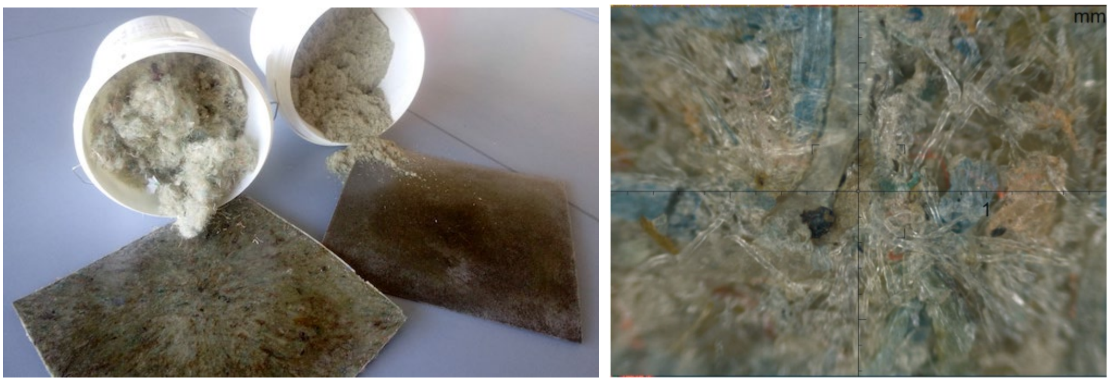

Fig. 6.13: Left: Plates were pressed from gillnet fibre material in different grinding qualities. Right: The microscopic image of the input material reveals a rubber fragment among the inhomogeneous fibre mix. (© Weißbach & Gerke 2018)

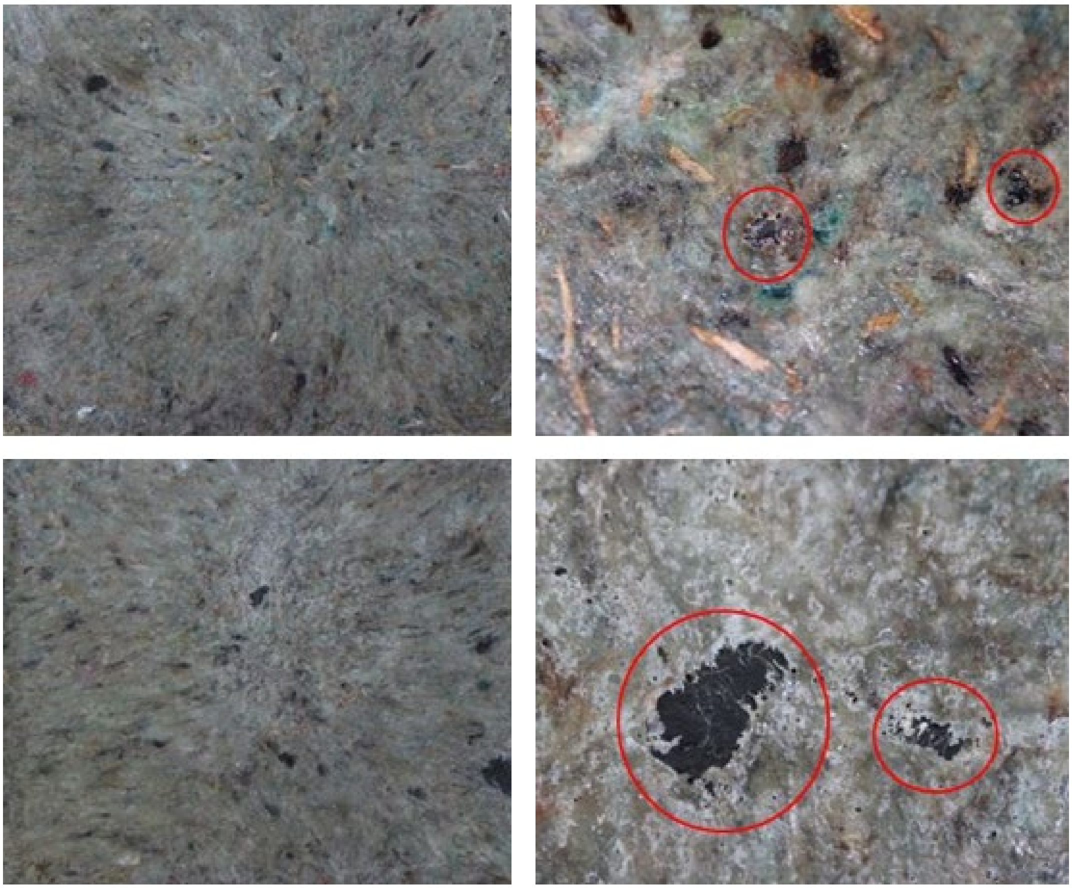

Fig. 6.14: Left: Plates pressed from gillnet fibre material after all cleaning stages at 240°C (top) and 230°C (bottom). Right: Microscopic analysis of the pressed plate reveals strong inhomogeneities and that the surface is not closed because rubber inclusions cause porous breaking points. (© Weißbach & Gerke 2018)

The origin of the rubber could not be identified. Rubber particles are omnipresent in the natural environment, e.g. from tire wear, but the large contamination fraction suggests one of the following origins:

1) DFG iself, e.g. cable coating from cables frequently present in retrieved DFG
2) Residual rubber fragments in machinery at Vecoplan AG, either in shredders or in the friction washer from previous trials with rubber.

Both rubber and lead contamination will also be problematic in any extrusion and injection moulding process. A high lead fraction leads to a high toxicity and renders gillnet-dominated DFG unsuitable for material recycling into consumer goods. Rubber contamination leads to breaking points that undermine the material stability desired in polymer products.

6.6 Discussion

The challenge with retrieved gillnet material is the highly diverse mix. In addition to four types of polymers, sediments, lead fragments, and organic matter contaminate the fibre samples. The polymer fibres trap these contaminants as they preserve loops and knots down to very small grain sizes. Although PP and PE could be extracted from the mix in the floating fraction during swim-sink separation, wood particles and other light-weight organic contaminants were still mixed with the polyolefin fibres. Wood would coke during the extrusion process and lead to black, brittle gaps in the granulate compounds and the final product. The high-density polymers PA6 and PET are most valueable for recycling due to their comparably high material value and abundant use in consumer products. PA6 dominates the gillnet material and was concentrated in the sink fraction after swim-sink separation. However, sediments and lead fragments were also singled out in the sink fraction. A second separation stage with saline solution did not allow concentrating the PA6 at the surface, presumably because the solution was not saturated. For an automated process, at least a 2-stage swim-sink separation with one high-density solution would be required to extract the economically valueable PA6 and PET fractions from the mix. Separation was likely impeded in particular by the fact that fishing net material forms loops and retains knots even down to grain sizes of 0.08mm. Fine-grinding at least to a grain size of 1mm is beneficial to allow for the most efficient contaminant and polymer separation.

Another complication for the extrusion into granulates is the mix of polymers. Even in automated processes, the polymer separation will not be perfect, and small fractions of low-density polymers PP and PE are expected to infiltrate the extracted

PA6 compound. The DSC analysis shows that the range of melting points spans almost a factor of two from 140 to 260°C. The PE and PP fractions melting at low temperatures will coke and blacken at the higher temperatures required to melt PA6 and PET. A material mix will cause a highly inhomogeneous polymer melt in the extruder. Together with wood and rubber fragments, the ash residuals render the resulting recyclates brittle and introduce breaking points. It should therefore be ensured that the high-density and low-density polymer fractions present in DFG are separated prior to extrusion. This will also improve the uniformity of material quality. On the other hand, revising the production process of plastic products is currently under extensive discussion. For fishing nets, avoiding mixed PE/PP lines would facilitate recycling of future nets. A simple way to separate the polyolefin floatlines from the main PA or PET netting and the sinkline would also be highly beneficial for a circular economy approach on fishing gear.

In summary, a clean separation of the retrieved gillnet material from the sea into its polymer compounds and the extraction of sediments, lead and other contaminants was not feasible even when fine-grinding the samples to 1mm or 0.08mm grain sizes. The complexity of the material implies that polymer extraction for material re-use is laborious and technically challenging. At the minimum, a high manual pre-sorting effort is required to remove lead lines and larger items. Ideally, the polymer material fractions identified during these trials (netting, floats and float lines, sinkline sheathing) should be manually separated prior to any recycling effort.

6.7 Summary of gillnet re-use options

The chemical and mechanical analyses confirmed the results by the external polymer laboratory (Sec. 4). Mechanical properties suggest the polymer components could be material recycled under the prerequisite that a better separation and washing technology can be developed. Residual fine-grained sediments were observed to cause extensive wear on cutting and grinding equipment. Because of the high degree of remaining impurities after multiple washing and density separation stages, the material was not tested for breaking and tensile strength. The inhomogeneity implied that non-reproduceable results would have been obtained. A larger number of test specimen was generated from homogenised samples by the Magdeburg Polymer Service Centre (MAKSC) as described in Sec. 4.

The following obstacles to material recycling were encountered:

- A high degree of residual contamination with sediments, lead, and organic matter
- Complex multi-component material mix containing at least 4 types of polymers
- Knots, loops and twists are retained down to very small grain sizes of less than 1mm
- Similar polymer densities of PA/PET or PP/PE impede clean separation into polymer fractions
- Contamination with wood and rubber fragments prohibits uniformity
- Organic matter such as wood and algae have similar densities as PP and PE
- Material mix is expected to result in inhomogeneous melts
- Diversity in polymer melting points results in coking of least thermally stable polymers during extrusion
- Recyclates are expected to have a high degree of brittleness and fracture points
- Fibres are not suited for electrostatic material separation
- Lead is spread during processing throughout the samples introducing toxicity.

The following minimum requirements can be given as recommendations for gillnet material processing:

- Lead lines have to be removed prior to any processing, in particular prior to shredding and washing of the fibres
- Removing visible contaminants is highly beneficial
- Identifiable different material types should be manually separated
- Lower-density and higher-density polymers have to be separated to avoid technical problems during material extrusion

The material recycling trials showed that gillnet-dominated samples are most difficult to recycle despite the comparably pure polyamide net material. Extensive pre-processing including removal of swim- and sink-lines and trapped waste such as cables would be required to allow for polymer recycling. Even with extensive pre-processing, fine-grained sediments and the fluffy consistency of ground PA fibres might impede material recycling. Automated material separation will be technically challenging, but would be a major asset when processing gillnet-dominated DFG. Such processes, however, would need to be developed, would be costly and currently not economically viable. Deriving a profitable recyclate from gillnet-dominated DFG is almost impossible. Only an extensive manual pre-sorting stage would allow the distribution of individual material fractions into the existing recycling channels.

7. Discussion & Conclusions

A detailed summary of the findings is given in the Executive Summary at the beginning of the document. In this discussion section, a few aspects are highlighted that have not been discussed in the individual chapters thus far.

7.1 Market value

One of the major aims brought forth by the MARELITT Baltic project is to develop guidelines for dealing with derelict fishing gear. Fishing nets are composed of synthetic materials such as PP, PE, and in particular PA (nylon), a high-value polymer on the recycling market. For new granulates, the market value of PA6 is with 1.7-2.0 Euro/kg twice as high as the market value of most other common polymers (PP, LDPE, HDPE, PS, PET) according to the raw materials market place www.plasticker.de. At the same time, PA monofilament fibres are particularly pristine as additives are not needed in the production process. An efficient separation and cleaning process would allow lost and discarded fishing nets to return into the production cycle as a valuable raw material.

Although with significantly lower market value, PP, PE and PET are large fractions in the retrieved DFG by weight. The twisted ropes and woven trawl nets are sturdier and the thick, woven fibres imply a much higher weight of individual fragments as compared to monofilament gillnets. After pre-sorting, the PA6 ropes provided a particularly uncontaminated material type that could easily be shredded. Friction cleaning turned out to be difficult because of the fluffing up of the rope fibres and the blockage in the Vecoplan system. However, the rope fibres that could be washed resulted in a very clean material that had the appearance and feel of raw wool. When these relatively pure materials can be generated from retrieved fishing gear, the introduction into the recycling chain will be easier than for the mixed polymer types, mitigating also the lower price profiles of non-PA polymers.

7.2 Aspects to be considered in the recycling process

All experiments suggested that a labour-intensive manual pre-sorting stage is necessary before the material can be processed further. While fibre shredding and magnetic separation of small metal fragments are efficient with existing shredders, density separation, extraction of toxic substances such as lead from sink lines, cleaning and regranulation proved challenging. The fluffiness of shredded fibres containing PA or PET causes other polymer fibres and contaminant fragments to be entangled in the fibre agglomerates. While sediments and lead fragments could be extracted using saturated saline solution as the first swim-sink bath, the separation of different types of base polymer fibres was not as efficient. An automated swim-sink separation stage, as is carried out at Plastix DK with discarded trawl material, would be required after an efficient cleaning process to allow for the separation of fibres of different base-polymer types.

The separation into the individual polymer components would be crucial for the regranulation of fibre materials and re-use in the recycling process.

7.3 Material quality & analysis

Analysis of the chemical content suggests that nets are predominantly composed of PA6 fibres. This has to be positively evaluated, as PA6 is a pristine material with a comparably high market value. In the PET ropes, contamination with other polymers and organic substances are found, rendering this PET material – in contrast to other PET recyclates – challenging for the recycling pathway.

7.3.1 Analysis of potentially harmful substances following REACH

The chemical analysis following the EU REACH protocol found the lead content to be a factor of 2-4 enhanced with respect to the acceptable limit of 100ppm in the EU packaging directive in 3 of the 5 analysed DFG samples. Washing and density separation had already decreased the lead concentration by a factor of ten at this stage. Lead contamination from sink lines has to be avoided to allow material recycling, and pre-sorting needs to account for this hazard. Two samples showed enhanced chlorine content, which could have originated either from cable mantling in retrieved DFG or from previously processed materials in the shredder or washer. During automated processing, a check for hazardous substances following the REACH protocol is therefore highly recommended.

All other chemical components were within acceptance levels of the EU REACH and packaging directives. This implies that hazardous chemical substances other than lead and chlorine are less likely to impede DFG recycling.

7.3.2 Analysis of physical properties regarding usability in mould-injection shaping and 3D printing

Extensive pre-sorting is required to extract uniform batches from the retrieved, mixed DFG materials. Especially, ropes and woven netting are more easily extracted and provide purer polymer fractions than gillnet materials because of the absence of attached swim and sink lines. The physical and mechanical properties of all samples are found to be comparable to recyclate specifications of end-of-life fishing gear granulates. The exception is the breaking strength, which is decreased in DFG-based test specimen due to impurities. The most challenging aspect encountered during extrusion trials was the fluffiness of PA6 and PET fibres. These high-value, high-density polymers tend to form fibre balls which are not pourable. Pourability is a prerequisit especially for smaller-scale extruders. In a large-scale extruder with a strong sucking screw, fibres would not cause blockage and air to be sucked in. Very fine grinding was found to improve the feeding of PA and PET fibres into the extruder system. With an efficient washing, sediment extraction and density separation and grinding system, DFG-based fibres are fit for extrusion into granulates that can subsequently be used for injection moulding and similar modelling techniques.

7.4 Conclusion

Recycling of lost fishing gear retrieved from the sea is a challenging and time- and effort consuming process. As no standardised methods and machines exist to process this material, the sample testing proved experimental and energy-inefficient. However, if local solutions and a recycling chain can be build up, recycling of some of the DFG fractions is feasible. In particular, if manual pre-sorting of different net materials and a first pre-processing stage, possibly even with small shredders and/or a pre-cleaning bath near the harbour, can be utilised, some of the retrieved ropes and netting would be valuable raw materials for granulation. While recommendations for building up such a functioning system are work in progress within the MARELITT Baltic EU INTERREG project, a combination of collections of aged, discarded fishing nets and retrieved DFG in fisheries harbours is likely the only efficient solution for the problems encountered with DFG recycling. An economically viable system based on retrieved fishing gear alone is unlikely to be established, especially given the inhomogeneous material flow and small amounts of nettings and ropes available from lost fishing gear retrieval actions. When sorting of end-of-life fishing gear takes place in the harbour, retrieved DFG can be incorporated into this sorting process. High-quality, uniform DFG could then be recycled along with comparable end-of-life materials, while contaminated DFG could be sorted out for thermal processing. Combining discarded and lost fishing gear during the recycling process would be desirable as fishermen would not only be involved, but might also have a longer-term interest in selling aged materials to the recycling industry. This could imply a long-term re-use effort for lost fishing gear in good, recyclable condition as well and would be in line with the requirement of waste fishing gear recycling in the recent proposal for the novel EU plastics directive.

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Links

Implementation Notes on the attribution of wastes (“Vollzugshinweise zur Zuordnung von Abfällen zu den Abfallarten eines Spiegeleintrages in der Abfallverzeichnis-Verordnung”), Berlin 2015, Appendix IV, Table 1: https://www.berlin.de/senuvk/umwelt/umweltratgeber/de/bekannt/pdf/abfallvollzug.pdf

Market value of lead scrap [Feb 13, 2018]: http://www.schrottpreis.org/bleischrott/

https://plastixglobal.com: Recycling company focussing on end-of-life fishing gear

https://bureo.co: Recycling company producing skate boards and other beach items from end-of-life fishing nets

http://www.econyl.com: Recycling company generating “econyl” yarn from pre-cleaned PA6 end-of-life and retrieved fishing gear, mixed with end-of-life carpet materials

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The MARELITT Baltic project

Derelict fishing gear (DFG) is addressed worldwide as a source of marine litter with extensive hazardous effects on the marine ecosystem. From 5.500 to 10.000 gillnets and trawl nets are lost every year and despite intense media focus – the problem is poorly known in the fisheries industry and among politicians.

The MARELITT Baltic project is one of the first transnational initiatives in the world to provide an operation oriented all-in-one solution for how to approach DFG. It will turn a diffuse problem into a clear and apprehensible topic that can contribute to an enhanced international readiness to act.

The project is divided into five work packages (WP), where package 2, 3 and 4 are the major parts concerning the cleaning, prevention and recycling of lost fishing gear.

Cleaning the sea and planning future action at sea
The aim of WP 2 is to plan and execute DFG retrievals in Sweden, Estonia, Poland and Germany both on the seafloor and wrecks. The activities will be based on methodologies and techniques tested in earlier national projects. These experiences will contribute to a common methodology which is crucial given the extreme hydrographic and morphological variation in the Baltic Sea. The new operation platform will make cleaning operations both transparent and demonstrate if the task is physically possible.

Responsible fisheries prevention scheme
The aim of WP 3 is to develop an overall approach to mitigate the problem of lost fishing gear in the future. It can roughly be divided into three types of actions. Firstly, the project will increase knowledge on fishing technological and strategic changes over time and how these changes have influenced the evolution of gear loss. In the second step, the project will focus on the potential causes to why fishing gears are lost. The third category of action includes development of preventive methods such as gear marking technologies helping to track irresponsible fishermen or assisting responsible fishermen to locate lost gears.

Marine litter reception facilities and recycling
The aim of WP 4 is to identify the options for a safe and fully sustainable handling and recycling of the lost fishing gear in a circular approach. Within this work package the phase from reaching the harbour through cleaning, sorting, transport until processing of recycling of the nets will be dealt with. The work encloses a variety of approaches such as creating a knowledge baseline about the transnational status and capacities of harbours, waste handling systems and industries in the Baltic Sea countries.

Projectpartners

Sweden
Municipality of Simrishamn, Lead partner
Keep Sweden Tidy

Germany
WWF Germany

Poland
WWF Poland Foundation
Maritime University of Szczecin
Kolobrzeg Fish Producers Group
Institute of Logistics and Warehousing

Estonia
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