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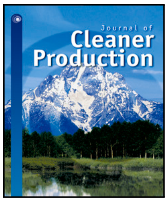

On-board and port 3D printing to promote a maritime plastic circular economy

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ABSTRACT

Oceanic plastic pollution has become one of the most serious problems in terms of the environment, and Circular Economy (CE) strategies are being implemented to reduce it. The article presents the results of a diagnosis of plastic waste in the maritime sector and the use of 3D printing as an enabling technology of CE around plastic. Maritime industries were asked about their plastic waste generation and potential parts and components which could be replaced by equivalent parts made by 3D printing. To close the CE loop, these parts would be printed with filament from the maritime industries' plastic waste. The article addresses this process of generating filament that enables the CE and how this printing process can be affected and corrected under on-board conditions. A polypropylene-based strapping tape waste was chosen to produce recycled filament. This filament resulted stiffer than the commercial filament and, through an additivation process, it achieved better flexural properties. Finally, the 3D printing process during on-board unstable conditions was improved by an automatic and electronic correction on the 3D printer machine itself.

1. Introduction

Plastic pollution has become one of the most serious problems in terms of the environment (Smith and Brisman, 2021). Besides other strategies to tackle this issue (Prata et al., 2019), the Circular Economy (CE) is being promoted and applied to the specific problem of plastic waste reduction (Hahladakis et al., 2020) by turning it into a resource (Smol et al., 2017). Different economic areas and governments are also addressing this problem through regulations and programs, in which the CE is recognized as a key strategy. For example, the European Commission and its "new Circular economy action plan" (European Commission, 2020) highlights the importance of recycling plastics and reducing their use, and mandatory requirements will be proposed as part of its "Strategy for Plastics in the Circular Economy and the Directive on Single-use Plastics".

CE principles are being applied in many different scenarios and industries and include such things as using fewer primary resources in the automobile and packaging sectors or changing the utilization patterns of resources in the building sector (Rizos et al., 2017). There are also many CE approaches and implementation strategies (Elia et al., 2017; Kalmykova et al., 2018) which range from a global approach (Bocken et al., 2016) to a more local focus, such as seaports (Carpenter et al., 2018).

A specific CE application scenario concerns marine plastic litter (Haward, 2018; Ronkay et al., 2021) which tends to accumulate in ports (ten Brink et al., 2016), on shores (Munari et al., 2016), in plastic islands (Debroas et al., 2017), and on the ocean surface and seafloors (Pabortsava and Lampitt, 2020). On land, populated or industrialized areas are the major sources due to littering, plastic bag usage, and solid waste disposal (Li et al., 2016). However, plastic waste is also generated by maritime activities: on-board activities during fishing campaigns, nautical activities, and aquaculture typically consume single-use plastics such as containers, synthetic ropes, and fishing nets (CE Delft and CHEW, 2017).

Among other manufacturing technologies, 3D printing (3DP) is recognized as a new tool for cleaner production in a CE scenario to reduce plastic pollution (Pinho et al., 2020). FDM (Fused Deposition Modeling) is the most common technology using plastic extrusion for 3DP (Ngo et al., 2018). It has become a popular, accessible, and cost-effective technology (DePalma et al., 2020). Other plastic-based industrial technologies such as injection moulding can also use recycled plastic as raw material (Ronkay et al., 2021). However, Injection moulding requires a minimum batch size to be profitable (Minguella-Canela et al., 2019).

Researchers have reported numerous applications of 3DP in different sectors such as aerospace, electronics, automotive, food, medical, or

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industrial machines (Jiménez et al., 2019), but it is not very common to find a use case of 3DP in the maritime field. Despite this, articles can be found in the literature about 3DP in this sector, such as (Kostidi and Nikitakos, 2017; Kostidi et al., 2021) where the benefits of 3DP of spare parts to reduce supplier waiting time are explored, or its application to on-board repairs in shipbuilding (Ziółkowski and Dyl, 2020), or for ropes and nets recycling through transformation to 3DP feedstock for the manufacture of local-scale products or special components for construction (Hunt and Charter, 2016). However, none of them addressed 3DP as a kernel technology for harnessing marine plastic waste and the CE to transfer the results to the main maritime industries (fishing, by-fishing, shipyards, port management, and the recreational sector).

The profitability of 3DP in this environment relies on the identification of products to be produced or repaired using these technologies, or with new and adapted versions of them (Green Ship of the Future, 2018). Furthermore, in terms of 3DP functionalities, the questions are whether 3D printing is suitable to support "in port-companies' operations", to support "on-board operations", and the specific requirements for both cases.

This is the framework of the European project EAPA_117/ 2018 CircularSeas (CircularSeas, 2020). The project is organized through a transnational consortium composed of six seaports: Ondarroa and Vigo (Spain), La Rochelle (France), Peniche (Portugal), Cork (Ireland) and Plymouth (UK). The project researches CE strategies for the reuse of plastic waste from the maritime and ocean environment through new adaptations of 3D printing technologies.

The work presented in this paper is based on the hypothesis that a significant amount of plastic waste is generated in the port environment. This environment is also a potential demander of plastics as a material for its processes. The article aims to identify potential parts and components which could be replaced by equivalent parts made by 3D printing and recycled plastic waste. It also addresses the process of generating recycled filament that enables the CE and how the 3D printing process can be affected and corrected under on-board conditions.

The paper is organized as follows. Section 2 addresses the Circular Plastic Diagnosis in one of the ports of the project to analyze plastic waste generation, the needs of maritime industries, and the opportunities and applications of 3D printing to ocean industry/port activities. Section 3 presents a use case resulting from the previous survey phase and answers two questions. First, can functional parts be printed from plastic waste generated by maritime companies? Second, how do oceanic conditions affect 3D printing of these parts and how could any negative effects be compensated? The article ends with a discussion of the results (Section 4) and conclusions about the research (Section 5). Alternatively, the reader can swap the reading order between Sections 3–4 and 2, allowing Section 2 for further reading on the origin of the decisions made in the technical development part of the materials (the use of strapping tape) and the use case (on-board 3D printing). Thus, the reader can broaden the pragmatic perspective of the actors within the case study area.

2. Circular plastic waste diagnosis in a maritime-port environment

This section presents the diagnosis of the generation, treatment, and current reuse of plastic waste generated by the maritime industries (fisheries and auxiliary fishing, shipyards, port management, and nautical companies) in the Port of Vigo. This diagnosis aims to address CircularSeas research issues about new economic scenarios and value chain configuration into the port environment around a CE, waste, and 3DP with recycled plastic. The methodology and the results of the diagnosis are presented below.

2.1. Stakeholders survey methodology

The survey was designed to gather data for the circular plastic diagnosis and was organized into five question packages: general information; waste identification and waste management chain; plastic-based products and non-plastic products replaced by greener ones; 3D printing; and general concerns.

The survey started asking for general information about the companies: type of sector, main activity, and current involvement in environmental sustainability and CE projects. The second part of the survey addressed the quantification and identification of waste generated by the maritime companies during their commercial activity. Therefore, the following information was requested for each waste identified: name, quantity, origin, type, and storage. Moreover, companies were asked about the waste management chain of each waste previously identified: current management process, agents involved, and type of agreement with the agent involved.

The third section of the survey addressed the possibility of replacing commercial products, which can be made of plastic or non-plastic materials, with green products made from recycled or biodegradable plastic. The survey analyzed the current situation of stakeholders' business activities to identify products with a high breakage rate or auxiliary products which they are interested in replacing with a greener option.

The fourth section of the survey explored the current or future use of 3DP as a manufacturing technology to support maritime industries: interest in 3DP, autonomy to perform 3DP from design to manufacturing, and conditions to use recycled plastic-based parts instead of commercial parts. Moreover, the survey included a question about on-board manufacturing with 3DP technologies.

Finally, the last section of the survey provides information about the general concerns of each stakeholder: current internal policies about plastic collection and valorization of plastic waste. The full interview questions are available in the supplementary data section.

2.2. Survey results

The data collection phase was performed by in-person meetings with each stakeholder associated with the Vigo Node in the CircularSeas project, where 35 relevant companies and institutions participated. The surveys provide significant results which are summarized in this section. They verify the wide range of plastic waste generated by each maritime industry and new green products to be produced by 3D printing.

The responses from the first part of the survey show that 88.57% of the surveyed companies have been involved either in some strategy or project related to environmental sustainability and the CE in general and 54.29% have specifically carried out plastic waste diagnoses. Within this 88.57% of companies, the environmental projects are focused on the optimization and efficient use of their resources in different processes, which include: cardboard packaging segregation; metal containers, plastics and bricks recycling; plastic caps segregation for social purposes; and the segregation of mollusks attached to ships hulls for the regeneration of degraded soils, among others.

Table 1 summarizes the results of the waste generation and waste management chain section, where a list of the main plastic waste identified is presented. The total amount for each plastic waste includes the combined contributions from all the responses.

As mentioned above, two situations are analyzed: plastic and non-plastic products to be replaced by a green product. The main plastic-based products identified are: spare parts (for instance, a bearing carrier), production and laboratory utensils, support parts, prototypes, plastic bottles, film packaging, plastic pipes, plastic containers, and plastic bags. However, other technologies such as injection molding or extrusion blow molding are more appropriate for the manufacture of plastic bottles, film, tubes, and bags.

Table 1
Main plastic waste identified and its management chain.

Waste	Quantity (Tn/year)	Plastic type	Origin	Storage method	Waste management process	Agreements on waste management
Nets	1681.34	HDPE, PP	Disused nets from extractive fishing vessels	Humid	Storage in special container for nets, Sale to plastic recycling company	One-time sale to a plastic recycling company, Collection by the port manager through annual tender
Containers	454.10	PET, HDPE, PP, LDPE	Glazing and empty containers of non-hazardous products	Humid, Dry	AWM[1]	Contract with private company for collection, transport and management of the waste
Films	135.75	LDPE	Receipt of materials, warehousing and material movement	Dry	Storage in yellow container, Sale to plastic recycling company	Contract/tender through the port authority with an AWM[1]
Bags	130.00	LDPE	Consumables for processing, storage and embassy	Humid	Compacted and managed as municipal solid waste	Annual contract through municipal government with an AWM[1]
Nautical rope	100.00	HDPE, PP	Productive process	Humid	Sale to company for reuse	One-time sale to second-use market
Fragile packaging	31.28	EPS[b]	Fish packaging	Dry	Collection by the port manager	Annual tender through the port authority with an AWM[a]
Strapping tape	29.56	PP	Raw material reception	Dry	Storage in yellow container, Sale to plastic collection company	Annual contract with private company
Containers with UP[c] resin	22.55	UP[c]	Raw material, Parts production	Dry	Special waste container	Annual agreement with an AWM[a]

[a] Authorized Waste Manager.

[b] Expanded Polystyrene.

[c] Unsaturated Polyester.

Regarding the possibility of replacing non-plastic products with greener products, stakeholders have mainly identified the following candidates: long parts (pallets and parts of a jetty), small parts (roller stops and support parts), and spare parts in multiple sizes, which is the most prominent product identified from the survey responses.

Analyzing the part of the survey covering the introduction of 3D printing technology, the responses show a positive interest in introducing this technology into maritime business activities (68.57% of respondents). In a sector historically reluctant to changes and to introducing new technologies in the maritime field (Kostidi and Nikitakos, 2018; Ziółkowski and Dyl, 2020), these results reveal a possible technology to be exploited.

The next question evaluated the companies' autonomy for carrying out the entire 3D printing chain (from modeling to manufacturing). Only 20% of companies surveyed have stated that they are capable of carrying out the prints themselves and 60% prefer that the responsibility for the creation and processing of files lies with an external service or company.

One of the goals of the project is to encourage companies to replace the commercial plastic they use in their business activity with recycled plastic. Throughout the responses, companies show an interest in using recycled plastic (68.57%). Within this 68.57%, 41.67% add that they would use recycled plastic if it were available and for short product runs, while the other 58.33% said that they would use it only if the benefit of using recycled plastic resulted in positive marketing or the delivery of hallmarks such as those showing the company supported the "Green Economy" and "Marine Plastic Reduction". Companies not interested in recycled plastic answered that they would employ recycled material only if legislators forced the reduction of commercial plastic on their production chain by law. These companies also remarked that they never use recycled plastic but could change their opinion in the future if recycled plastic were profitable in terms of process improvement, energy savings, or if the material had approval from a certifying agent for its safe use in terms of mechanical and hygiene requirements. The last question in this part of the survey, the introduction of on-board manufacturing with 3D printers in order, for example, to carry out on-board repairing while traveling, was positively evaluated by 20% of the companies.

Finally, 22.86% of the surveyed companies have internal policies to reduce the generation of waste and improve the performance of their machines, segregation into different types of waste, and relationships with different waste management entities. Moreover, respondents highlight two concerns about the current recycling policies. The first is the limited number of programs for the maritime sector regarding management of wastes from their commercial and industry activities, and the second is the lack of stronger policies that promote the use and collection of plastic from maritime industries.

2.3. *Survey results analysis*

From the survey, it can be seen that companies in the maritime sector are increasingly aware of environmental sustainability and the generation and management of their waste. Waste generation data emphasizes that there are many types of plastic waste in many types of products but there is little plastic waste that is currently being recycled. For instance, waste treated as Municipal Solid Waste (discarded to green and yellow containers) is not valorized and it can become part of a circular use case by using 3D printing technologies, as stated in Nascimento et al. (2019). Nevertheless, all of these plastic wastes could be reintroduced into maritime industries by manufacturing green plastic products.

The list of green products identified above shows the possibility of developing 3DP systems which would be required for their manufacture, making it more flexible, accessible, and adaptable to maritime industries. A special case concerns the replacement of wooden pallets with plastic pallets. Plastic pallets are especially in demand due to the sanitary requirements of some industries such as food (Deviatkin et al., 2019). However, due to their size, a more suitable and less expensive technology than 3D printing can be used to manufacture pallets, such as injection molding (Lay et al., 2019). Nevertheless, 3D

Fig. 1. Example of spare part: square bearing housing; (a) Commercial part assembled in a conveyor belt in a fishery's factory; (b) Recycled part made from plastic waste by 3D printing technology.

printing technology may have room even for products of this kind when facing customization to specific scenarios and with the arrival of the new generation of 3D printers.

From the survey results, companies would need a cheap and user-friendly infrastructure to carry out the whole printing process by themselves. This points to the need for a new business model based on services, which is also highlighted in the literature (Green Ship of the Future, 2017; Kandukuri et al., 2019; Kravchenko et al., 2020). Moreover, an opportunity to introduce the CE-3DP into the sector would ensure companies that recycled parts have certain conditions (quality, classification, norms) that compete with traditional parts (Kostidi and Nikitakos, 2018; Kandukuri et al., 2019; Kostidi et al., 2021).

Finally, surveyed companies that employ boats in their activity, such as fisheries, have agreed that they are not considering on-board 3D printing for the manufacture of spare parts with current technology. However, they also admit they minimize on-board stock of spare parts to maximize more fish storage, but when they need a specific spare part, they have to order from a supplier and wait for it, a situation that is also discussed in Knulst (2016), Green Ship of the Future (2018). Therefore, 3D printing to manufacture spare parts on board would be an option to consider as long as fisheries decide to make room for the necessary equipment and thus minimize the waiting time for a spare part. Other types of boats, and parts to be on-board printed have been identified: in general, highly technical boats that are at sea for long periods (i.e., oceanographic boats) are a clear example. Examples of 3D-printed parts for oceanographic use can be consulted at Mohammed (2016). Considering all the information gathered and analyzed, the developments are presented below.

3. Turning ocean plastic waste into 3D products for maritime industry: a Circular Economy use case

The analysis of the survey results pointed out that 3D printing to manufacture some spare parts could be an option to consider by maritime industries like fisheries for several reasons. For instance, to reduce the space on the boat to store the spare parts stock in order to minimize the waiting time for a spare part coming from suppliers. If some parts were manufactured by 3DP under demand, storage space could be smaller, both on board and/or in the maritime industry's facilities in port. The use of recycled filament for these 3D printing processes could be also an option for commercial reasons and/or just because of environmental concerns. Finally, maritime companies would close the 3D printing CE loop if they used recycled plastic from their plastic wastes, instead of commercial filaments. Fig. 1 shows an example of a potential spare part made of recycled plastic waste by 3DP.

However, the recycling process requires time, effort, and expert materials knowledge, and goes beyond a mechanical activities sequence of grinder and extruder (Mikula et al., 2021). Maritime industries have no intention of performing this process on their own, as it is far removed from their business. As an alternative, a specialized recycling agent (Pavlo et al., 2018) could enable the CE by obtaining filament from plastic waste (from on board or on shore) so that it can be reused in additive manufacturing technologies (Cruz Sanchez et al., 2020).

Next, Section 3.1 evaluates a use case of generating filament from maritime plastic waste to obtain parts for the maritime industry (onshore or on board) with similar qualities if industrial filament were used. Section 3.2 addresses the case of on-board 3D printing, where environmental conditions must be considered. Changes in the horizontality conditions are likely to affect the on-board 3D printing, as long periods are required to print medium size parts. The analysis of how the movement of the boat has an effect during printing and if there is a way to correct it is detailed below.

3.1. Material recycling

The residue of PP strapping tape (Fig. 2a) was chosen for the implementation of this scenario for several reasons: high volumes are generated in Vigo port (almost 30 Tn/year as mentioned in Section 2.2), its traceability and repeatability regarding polymer type are assured and it presents a relatively low impurity level, which eases the pretreatment of the material. Furthermore, the CE loop will be closed within the same company if spare parts are printed with recycled filament made from its own plastic waste.

The strapping tape was cleaned with warm water, which was enough given the above-mentioned low impurity level of this residue. In fact, the specific kind of strapping tape identified in Section 2.2 does not include any applied adhesive, which eases the recycling process of the residue. This type of tape is used, for example, to strap loads to pallets. In other cases, such as that of fishing nets, more comprehensive cleaning is necessary, which includes additional cleaning stages and the use of shear, in order to eliminate all the organic dirt and salt. The material was dried before processing at 80 °C for 4 h to remove all humidity.

The material was fed directly into the hopper of a single screw extruder (PAGANI MP.O. 30/25D) because including a shredding step was found non-beneficial for the feeding to the extruder due to the resultant low apparent density of the shredded material. Four to five strips were fed to the hopper at a time, in order to maintain a stable feeding amount. The extruder operated at 27 rpm and a temperature profile between 190–225 °C was set during extrusion. The molten polymer is forced through a 3 mm die, and then passed through a water cooling bath before being put into a Brabender Peletizer Type 881207 with pulling and pelletizing speed control, resulting in pellets of 2 mm diameter (Fig. 2b).

The pellets were dried in a Moreto D3TW dehumidifier for 2 h, 80 °C to eliminate water presence coming from the cooling bath, and then was subsequently transformed into filament with a diameter of 2.85 mm (Fig. 2c) using a 3Devo Filament Extruder. The extruder operated at 8 rpm screw speed, with a temperature profile of 215–240 °C and 20% of fan value for cooling.

Printing trials were carried out with standard geometries for flexural and tensile testing following the UNE 116005 Standard (UNE, 2012) (Fig. 2d) with an Ultimaker 2+ Extended printing machine. Samples

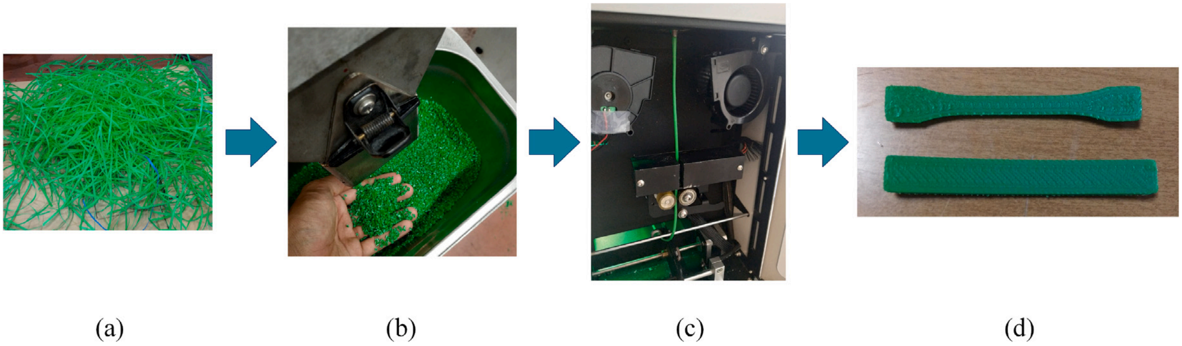


Fig. 2. Recycling process steps of strapping tape; (a) Strapping tape waste after cleaning with water; (b) granulated material after extrusion; (c) filament produced from the pellets; (d) specimens manufactured with 3D printing technology.

were printed using a 100% infill, printing speed of 60 mm/s, 235 °C and 85 °C printing and bed temperature respectively, and a nozzle of 0.6 mm. A PP-based tape was bonded to the printing bed before printing trials since PP adheres only to PP surfaces (Spoerk et al., 2018).

The same testing specimens were manufactured using a commercial PP Filament from Smart Materials (Smartfil PP) for comparison purposes. To reduce warping effects in the recycled material, a formulation was developed based on the pellets obtained after the first extrusion process (Fig. 2b). Different fillers have been proven effective to reduce warping effects in different manufacturing processes, such as injection molding (Jachowicz et al., 2014) or 3D printing (Spoerk et al., 2019). Calcium carbonate ($CaCO_3$), an inert filler widely used in industry, was found to reduce the warpage of 3D printed non-recycled PP (Dong et al., 2019). Based on that, a $CaCO_3$ Calprec PR from Cales de Llierca was added in 10 wt% together with 5 wt% of maleic anhydride (MA) grafted PP from Sigma-Aldrich containing 8–10 wt% MA, in order to improve the interfacial adhesion between the recycled PP and the filler. The compounding of the materials was carried out in a Labtech LTE 26–40/22 Kw twin screw extruder, with a temperature profile of 200–235 °C at a screw speed of 170rpm. The obtained pellets were processed to filament first and to 3D printed specimens afterwards.

The determination of mechanical properties was executed in an Insight (MTS Systems, Eden Prairie, Minnesota, USA) universal testing machine under controlled laboratory conditions (23 °C and 50% RH). Tensile properties were determined according to ISO-527 standard (ISO, 2019b). Three to five specimens per material were tested with an initial speed of 1 mm/min to determine the elastic modulus and increasing afterwards to 50 mm/min for the materials with high strain, and to 5 mm/min for more rigid materials until final break. Flexural tests were conducted according to the ISO 178 standard (ISO, 2019a) with a speed of 2 mm/min and a span of 64 mm with five replicates per material as well.

3.2. On-board 3D printing

The manufacturing of parts through 3D printing processes has to consider specific usage conditions in maritime and port production environments. For instance, saline and potentially dirty conditions mean that the machines have to be manufactured with suitable materials to fight negative effects such as corrosion (Wiener and Salas, 2005). However, this is only for machinery directly exposed to water or marine products, but not for computers and other common electronic devices, used without any adaptation to work in a port environment. Moreover, for the specific case of on-board conditions, computers need to have some modifications to overcome issues, such as humidity, saltpeter, dirty air, unstable swell, electricity shut-offs, vibration, breakages, etc. Therefore, anti-rust materials to overcome corrosion may be advisable, as well as uninterruptible auxiliary power supply systems to prevent uncontrolled power outages in machines (3D printers), and inertial measurements units that help the 3D printers self-adapt to unstable conditions, etc. Ziółkowski and Dyl (2020).

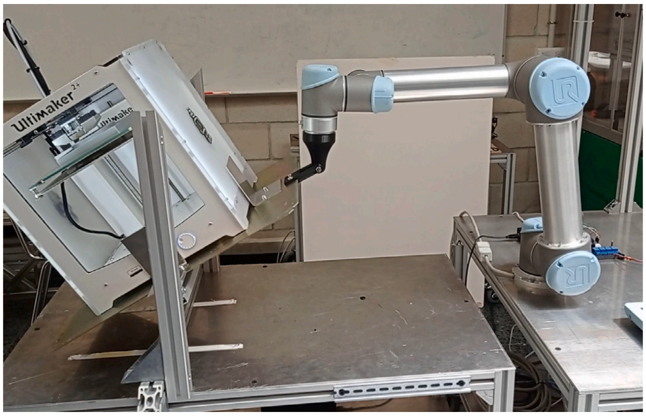


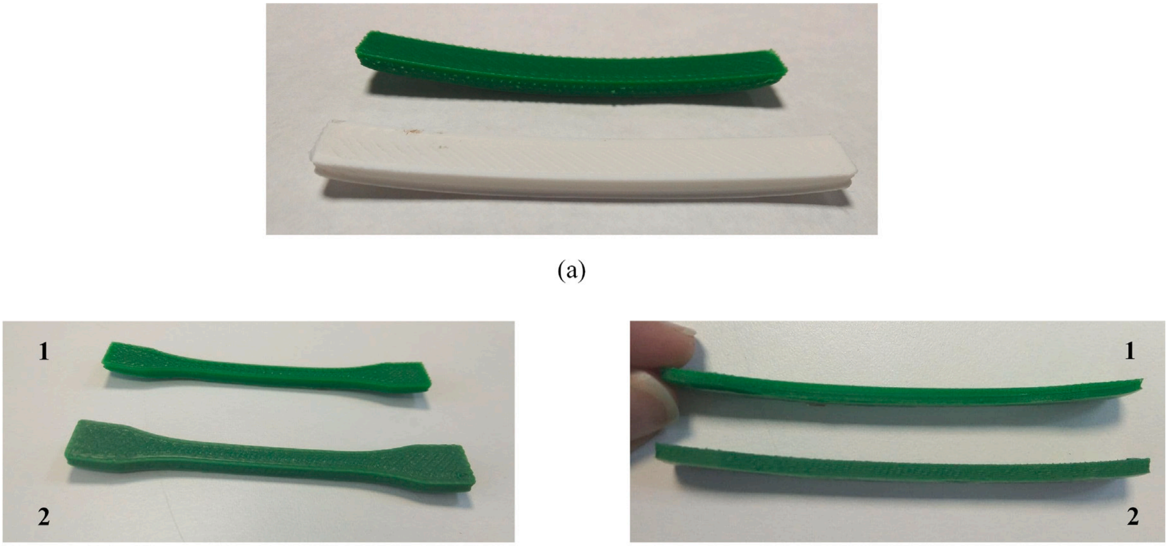
Fig. 3. Test platform.

From the control point of view, the 3D printer has to prevent sudden power losses to avoid discarding parts during the printing process. The possibility of printing in unstable conditions (like waves) is another operational factor that should be pointed out. In this case, printers could react by causing an interruption if the balancing threshold is exceeded, since the quality of the part may be worsened, or by providing speed corrections.

To study these horizontal changing conditions and their effect on the printing work, the experiment described in this paper was performed. A set of test parts was designed according to the UNE 116005:2012 (UNE, 2012) standard for additive manufacturing for test specimens that will be subjected to flexural tests (according to ISO 178) (ISO, 2019a). These parts were printed under four different conditions: normal-stable conditions, instability, instability with correction increasing the speed, and instability with correction decreasing the speed.

The 3D printer used is an Ultimaker 2+ and the material was “Ultimaker Polylactic Acid (PLA)” filament with a 2.85 mm diameter. The test parts were printed with vertical orientation and with the following manufacturing parameters: standard printing speed of 60 mm/s, a layer height of 0.15 mm, three wall lines, 15% fill density, lines fill pattern, and temperatures of printing and hot-bed of 210 °C and 60 °C, respectively. All these tests were carried out with commercial amorphous plastic (PLA) instead of recycled plastic in order to study the effect of horizontal wave instability solely. Thus, tests were isolated from other external disturbances provoked by working with recycled plastic, e.g., heterogeneity of the material and warping effect of PP.

The first of the test parts (“1N” test) was printed under normal conditions. The second (“2U” test) was performed with changes in its



(a)

(b)

(c)

Fig. 4. (a) 3D-printed flexural specimens made of strapping tape-based recycled material (green) and commercial filament (white); (b) 3D printed tensile and (c) flexural specimens made of non-modified strapping tape-based recycled material ("1") and the modified material ("2").

Table 2
Tensile and flexural testing results.

Sample	Tensile properties			Flexural properties	
	Peak stress (MPa)	Strain at break (%)	Modulus (MPa)	Peak stress (MPa)	Modulus (MPa)
Commercial filament	17.62 ± 0.26	824.22 ± 95.52	984.74 ± 129.31	16.32 ± 1.11	652.64 ± 31.93
Recycled Material (RM)	27.59 ± 2.27	9.09 ± 1.57	1757.43 ± 140.00	27.06 ± 3.36	999.01 ± 131.36
RM with additives	28.28 ± 0.50	10.25 ± 1.37	1913.92 ± 153.90	32.58 ± 3.06	1462.11 ± 145.91

horizontality, by means of a platform driven by a UR5 collaborative robot that emulates oscillations on a boat's deck during printing, as can be seen in Fig. 3. The tilt motion performed with the robot was from −40° to 40° with a movement speed of 250 mm/s and acceleration of 1200 mm/s^2, for 120 s from layer 230 of 536. Next, two tests were carried out modifying the nominal printing speed and studying if it is possible to compensate the effect of the disturbance. Therefore, a test was conducted increasing the printing speed by 50% (90 mm/s) and another by decreasing it by 50% (30 mm/s), "3+V" and "4-V" tests respectively.

Flexural tests were also performed according to the ISO 178 standard (ISO, 2019a) to compare the mechanical properties of the test parts and find whether the correction action implies an improvement or a deterioration of the mechanical properties beyond the appearance. Tests were made with five test parts of each type. These tests were carried out on an Insight (MTS Systems, Eden Prairie, Minnesota, USA) universal testing machine at controlled laboratory conditions (23 °C and 50% RH) with the following test parameters: 64 mm distance (span), 2 mm/min speed and a temperature of 23 °C.

4. Results and discussion

4.1. Material recycling

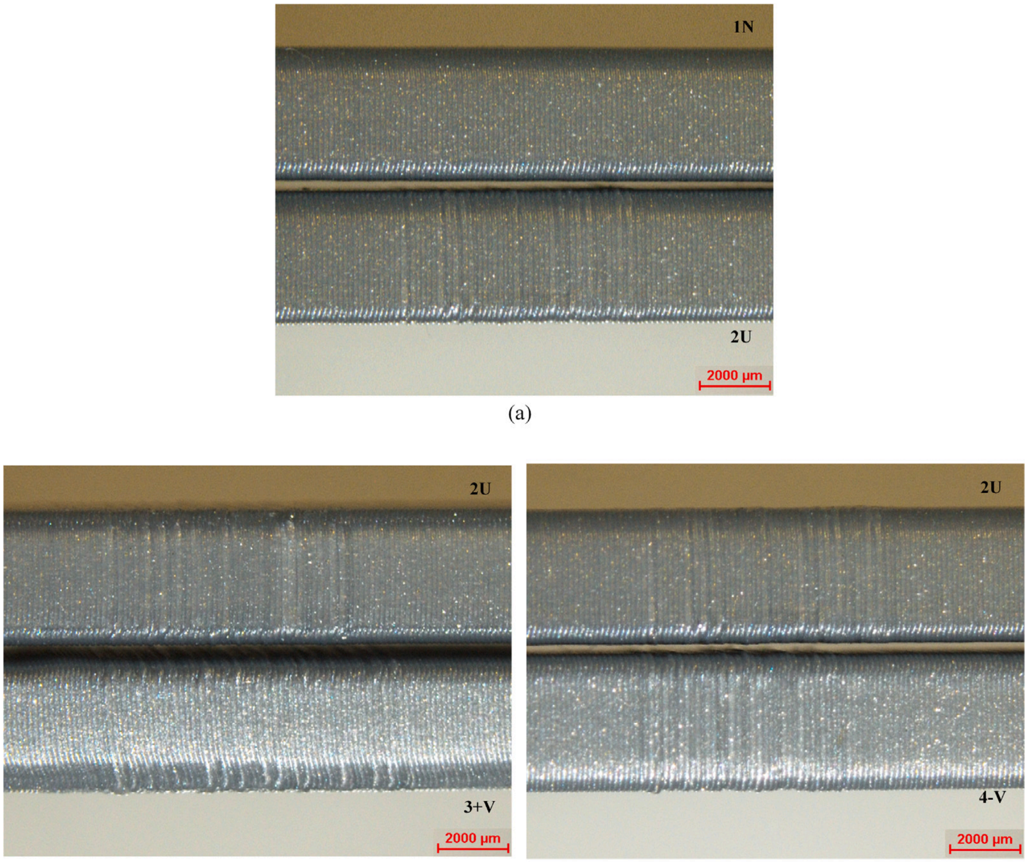
Fig. 4 shows tensile and flexural printed specimens of the commercial material (white specimen) and both non-modified (100% recycled strapping tape) and modified materials based on the recycled material. Both commercial and recycled materials show warping effects after cooling, due to the intrinsic properties of the polypropylene regarding thermal shrinkage (crystallization) (Jin et al., 2018), which causes the detachment of the material from the building bed. However, it can be observed that this effect is more pronounced for the recycled materials. It should be pointed out that the commercial material is optimized for the 3D printing process (probably incorporating additives to enhance printability, and selecting a PP grade of relative low crystallinity), unlike the waste used for the recycled material development, which is a high molecular weight/extrusion process intended grade material.

Even though the warping effect is not completely eliminated, it is reduced through additivation, as can be observed in the endings of the specimens. In the case of the non-modified materials ("1" in Fig. 4b and Fig. 4c), the thickness of the end sections is reduced, since the lower layers tend to peel off from the printer bed, hindering a proper layer deposition of the upper layers. This effect has been improved through the addition of fillers in the modified formulation ("2" in Fig. 4b and Fig. 4c).

The results of the mechanical testing can be seen in Table 2 (for raw data details see Supplementary Data section). They show that the material based on recycled strapping tape is stiffer than the commercial filament. It also features both higher tensile and flexural modulus, and higher peak stress. These properties are comparable to those used for the original application of this material, that is, extrusion of strapping tape. In contrast, the strain at break is much lower than that of the commercial material.

The comparison between non-modified and modified formulations shows comparable results for tensile properties, but an increase in flexural properties for the modified materials is observed. These results indicate that the approach used improves the properties of the material while reducing warping effects.

These results also show the potential of using recycled strapping tape to manufacture spare parts. The strapping tape-based recycled material features both higher tensile and flexural modulus, and higher peak stress than the commercial material, probably because it is an



(a)

(b)

(c)

Fig. 5. Test parts. (a) Comparison between a printed test part under normal conditions ("1N") and under instability ("2U") at "nominal" speed. (b) Comparison between the test part with compensation for speed increase ("3+V") and with "nominal" speed ("2U") both subjected to disturbance. (c) Comparison between the test part with compensation for speed decrease ("4-V") and with "nominal" speed ("2U") both subjected to disturbance.

extrusion grade with high molecular weight, optimized for that process and not for 3D printing. In contrast, the strain at break is much lower than the commercial material. Depending on the application, a more rigid material can be of advantage, as in the case of potential spare parts for maritime industries; however, the lack of strain properties might result in higher warping effects during 3D printing. Modifying the formulation of the recycled strapping tape through the addition of CaCO3 in combination with MA-grafted PP reduces the warping behavior of the material while increasing its flexural properties, which will help towards the use of recycled strapping tape for 3D printing in maritime environments.

4.2. On board 3D printing

The results and analysis of the 3D printed specimens in terms of both surface quality and mechanical properties are presented below.

Fig. 5 shows the surface quality comparison between the different printed test parts in the four cases analyzed. The test specimen printed in the "2U" case shows a different surface appearance under normal conditions as a result of the unevenly deposited layers. Fig. 5b also illustrates how the test specimen printed at higher speed obtains a slight improvement in surface quality during the intermediate runs ("3+V" case) compared to the one printed without speed changes ("2U" case). However, the finish is noticeably worse at changes of direction (corners), with a concave layer deposition. The comparison in Fig. 5c shows that the test specimen printed at a lower speed ("4-V" case) shows a more irregular deposition of the layers, with the worst final appearance.

A more uneven deposition of the layers is observed when the system is subjected to the disturbance, causing a rougher surface texture. Movements in the printer's location (on board) may produce, depending on the printer's mechanical configuration, vibrations in the structure, head, and print bed of the printer. These vibrations cause the inter-layer interfaces to become wavy, which in turn causes phase differences between two adjacent interfaces and uneven yarn thicknesses, as stated in Chen et al. (2022). This study also demonstrated the difference in the quality of vertical specimens subjected to different vibration frequencies, with specimen quality results consistent with those of this article. Furthermore, Afonso et al. (2021) suggested that the instabilities of the movement, irregularities in the synchronism between movement and extrusion and the control system may produce slippage of the filament, affecting the surface finishes of the intermediate and corner sections.

In general, a slower printing speed tends to produce a higher quality surface roughness (Meram and Sözen, 2020). Thus, reducing the feed rate would improve the surface finish. However, if the printing speed is too slow, as studied in this article by halving the printing speed ("4-V" case), the surface may deform due to the nozzle remaining in contact with the print layer for a prolonged period of time, as stated in Biglete et al. (2020). Moreover, extended exposure to the material deposition zone hinders heat dissipation, leading to greater material degradation and inferior surface quality (Valerga et al., 2016). In the case of an increase in speed ("3+V" case), the head spends less time near the material deposition zone, favoring heat dissipation and degrading the material to a lesser extent, providing better surface quality results. Therefore, the strategy of increasing the speed, which is used in the "3+V" test, slightly improves the surface quality of a printed part (Fig. 5b and Fig. 5c).

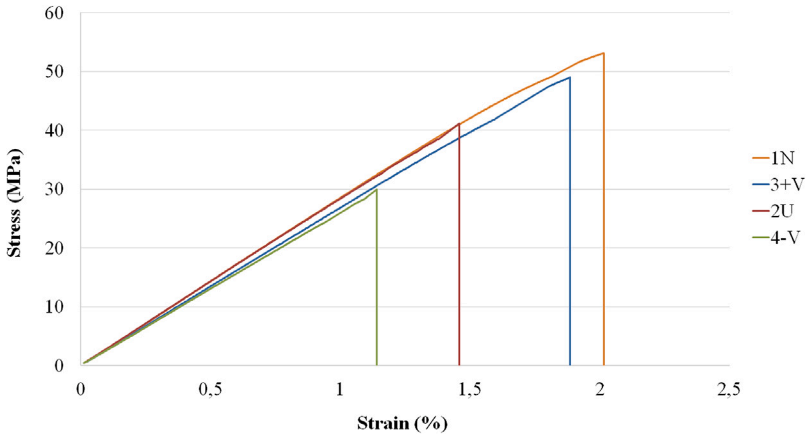


Fig. 6. Stress–strain curve from the flexural tests of PLA specimens.

Table 3
Mean results of the flexural tests with standard deviations.

Probe	Peak stress (MPa)	Strain at break (%)	Modulus (MPa)
1N	53.12 ± 3.20	2.13 ± 0.22	2841.74 ± 15.32
2U	40.64 ± 7.33	1.51 ± 0.29	2864.31 ± 25.10
3+V	48.36 ± 6.04	1.99 ± 0.28	2686.53 ± 83.33
4-V	28.90 ± 5.02	1.16 ± 0.16	2597.18 ± 62.89

Concerning the second part under study, the mechanical properties of the printed parts, Table 3 compiles the results obtained from the flexural tests (for raw data details see Supplementary Data section). The following Fig. 6 represents the stress–strain curve obtained from the flexural tests comparing the average values for each type of test executed.

Based on the tests carried out, it was found that performing oscillations during the printing process without changing speeds (“2U” in Fig. 6) worsened the mechanical properties of the specimens compared to printing without oscillations (“1N” in Fig. 6). This may be explained by the vibrations caused by oscillations, which reduce the viscosity of the material and bring downward inertial force, thereby affecting the porosity of the parts and worsening the inter-layer bonding performance, as reported in Chen et al. (2022). All these factors, in turn, negatively affect the mechanical properties of the specimens printed in the vertical direction.

The experiment (Section 3.2) explored the cases of increasing and decreasing velocity during oscillatory motion (“3+V” and “4-V” cases). Fig. 6 shows that increasing the speed improves the flexural strength compared to the “2U” case. This finding is consistent with the literature. Sun et al. (2008) reported that when the nozzle spends more time near any build region during printing (short span lengths), it produces higher overall build temperature, lower porosity, better bond strength between adjacent filaments, and thus higher flexural strength. So, the increase of the speed in the “3+V” case resulted in a longer nozzle dwell time over the printed region, leading to reduced porosity caused by oscillatory movement and improving the flexural strength of the printed parts. The effects of printing velocity were also analyzed by Pan et al. (2016). The study found that the bonding strength increased as the printing speed rose in a vertical cylinder printed using pure PLA due to the minimization of material stacking.

Regarding the case of decreasing speed (“4-V”), Fig. 6 shows that the mechanical properties of the vertically printed part are significantly worse. Generally, lower print speed gives better bonding and interaction between contiguous filaments, leading to an increase in tensile and flexural strength. However, the strength and ductility can be affected if the print speed is too slow, as the prolonged inter-layer cooling time causes the recently deposited material to cool down at a lower temperature, hindering the fusion of the thermoplastics (Gao et al., 2022). Considering that the porosity and inter-layer bonding performance is worsened by the effects of oscillatory movement, this slow movement also worsens its flexural strength, which is in accordance with the results obtained in Table 3.

Finally, although the strategy of increasing the printing speed improved the properties, they did not match those achieved by printing under stable conditions (“1N” in Fig. 6), but results closer to the ideal situation were obtained.

5. Conclusions

The article shows the potential contribution of 3DP in order to achieve a significant CE around recycled plastic in the maritime industry. As with many industries in the maritime sector, fisheries carry out their productive activity both on land and on board, and thus on-board manufacturing was also studied. Both approaches expand the use of 3D printing in the sector, the former being relevant in reducing the consumption of virgin plastic and reusing its own waste, and the latter expanding the use of printers not only on land, but also on board to manufacture parts such as spare parts.

The survey (Section 2) has brought empirical evidence for the economic and environmental viability of 3DP technology in manufacturing parts using recycled materials, while Sections 3 and 4 focus on empirical technical feasibility. The presented CE use case around 3D printing of spare parts (such as a square bearing housing in Fig. 1) shows that the recycling process of PP-based strapping tape waste is feasible, and the resultant material features adequate mechanical properties for component manufacturing after the addition of fillers to reduce warping effects. As the manufacture of components could happen on board, the article also deals with the specific condition of changing in horizontality during an on-board 3D printing process, showing that the process can be improved by electronic active corrections (speeding up) without the need to use external mechanical stabilizers.

It has been shown that there is a remarkable volume of plastic waste generated by the different target maritime industries. However, the potential impact will depend on a “broad system” approach in which many plastics are used to manufacture a wide variety of individual spare parts that are printed in a range of companies with very different business activities, achieving a greater amount of revalorized waste. Although the size of the port area will be a conditioning factor, if it is all included in this CE approach, the total number of potential parts for printing will make the system more feasible, both in the case study area and the entire maritime sector.

As future work, recycled materials developments should focus on formulation strategies to reduce warping effects after the 3D printing process. Finally, speed adaptation algorithms considering the change in horizontality, the type of trajectory to be conducted and the remaining path to travel during printing could be studied in detail to arrive at a solution that optimizes the surface quality and the mechanical resistance of the parts in the case of on-board 3D printing.

CRediT authorship contribution statement

Diego Silva: Data curation, Formal analysis, Investigation, Software, Visualization, Writing – original draft, Writing – review & editing. **Julio Garrido:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Writing – original draft, Writing – review & editing. **Blanca Lekube:** Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Alex Arrillaga:** Conceptualization, Funding acquisition, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.jclepro.2023.137151.

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