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MATERIAL DESIGN FROM INDUSTRIAL WASTE: AN EDUCATIONAL APPROACH

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ABSTRACT

Industrial design students are increasingly required to understand circular economy practices to produce more sustainable designs. One of these practices is waste minimization, which may involve reusing or remanufacturing residues. This article describes a project where waste materials from local industries were used to develop new materials, providing circular economy solutions. The project was conducted as part of third year Material Technologies and Sustainability courses in an Industrial Design Engineering programme, in collaboration with local industrial partners.

Over the course of four years, with four different waste inputs and a total of 180 students, the project resulted in the development of 12-20 suggestions for new materials for each industrial waste used. Of these results, 3 proposals for each material application were considered viable, environmentally beneficial, and interesting enough for further development. The project let students experience the difficulties of repurposing residues and showed that the developed materials aren’t always more sustainable than their primary material counterparts. Students were able to learn about material properties in an interactive way, which could be useful for other Industrial Design Engineering academics looking to incorporate waste recovery into their educational practices.

Keywords: Industrial waste, material properties, industrial collaboration, circular economy

1 INTRODUCTION

Circular economy (CE) is a broadly established concept in sustainability, where waste and pollution are minimized, and resources are conserved by recirculating them into production to create closed-loop systems. Much research has gone into this field, with more than 114 reported definitions for CE [1]. Despite the proliferation in definitions, it has gained traction and has been incorporated into national and regional policies around the globe [2], [3]. The European action plan for CE even states that by incorporating circularity principles into the process of product design and manufacturing, designers can help create more environmentally friendly products that are efficient in terms of resource usage [3]. Therefore, it is seen as crucial to educate designers into CE principles, and one of the common strategies used in education and spontaneously by students, is to develop things from discarded materials [4], [5]. Education for the implementation of CE is seen as a subset of Education for Sustainable Development (ESD) [6]. Even if it addresses a specific aspect of ESD, the education for CE is rooted on the same principles and frameworks (e.g., systems thinking, complex socio-technical systems). A review of educational approaches for CE and ESD extracted three principles for the development of educational material applied: interactivity (learning by doing something rather than just listening), non-dogmatism (presenting both positive and critical views towards a subject), and reciprocity (continuously incorporating student feedback into the programme) [6]. To apply the interactivity principle, a common approach used is to challenge students to develop new materials and/or products using waste [7]–[9]. This real-world challenge is currently faced by industry when trying to prevent and/or minimize their waste generation and is therefore a useful skill. However real implementation of the ideas developed in the classroom tends to be difficult to accomplish [7].

This article reviews the implementation of a challenge to design new materials from industrial waste, applied in two third year Industrial Design Engineering (IDE) courses. It is presented as a new case study in this field, in the hopes of corroborating and/or challenging conclusions taken by similar educational experiences referenced above.

2 MATERIALS AND METHODS USED

This article reviews the materials designed from industrial waste over the last 4 years of doing this assignment. The final project reports and resulting prototypes were used to evaluate student proposals. The authors, all teachers involved in these courses, converted their academic evaluation of student work into the following three assessment criteria:

- **Technical viability:** Considers the potential for industrial scalability of the proposal, including few and simple production steps, little additional material, large quantities of the residual material, and potential application areas where the material implies an added value. This criterion has been influenced by the feedback obtained from the collaborating industries during the courses.
- **Material Circularity:** Considers how recyclable (technical cycle) or compostable (biological cycle) the proposed material is. Recyclability is considered slightly better since the material is kept in circulation, rather than "dissolved" as nutrients.
- **Environmental Impact:** Considers how much environmental benefit is obtained from using the developed material instead of an existing similar material on the market, for a given application.

Student results are evaluated with these criteria, using a 1-5 scale, with 1 being the worst evaluated and 5 the best. Combining the three evaluations, each project could obtain a maximum of 15 points.

2.1 Structure of the educational experience

The experience described in this study is linked to two courses that run in parallel for 3rd year IDE students. The first course, "Advanced Materials I", focuses on designing, developing, and characterizing materials by revaluing industrial waste. Students are encouraged to design "tailored" properties, using advanced materials that are increasingly present in the industrial reality, such as composite materials. Once they develop a material, the resulting properties are analysed and characterized at the laboratory and relevant fields of application are identified. The experience-based learning with new materials serves as a tool to facilitate the inspiration phase and help students conceptualize and develop new, innovative products with high value contribution. The specific competencies that the course seeks to impart, are from the material technologies branch, and include the use of creative processes in idea generation, applying knowledge of materials, technologies, and production processes to develop new products.

The second course, "Advanced Materials II", defines advanced materials as sustainable ones. The specific competencies the course imparts are about sustainable design, including the understanding of key sustainability concepts, relate sustainability to the use of materials and resources, quantitively assess a product's environmental impact, and to creatively propose design improvements to reduce the environmental impact. It builds on "Advanced Materials I", so students are required to identify an area of application for the developed material, propose a product, and develop a Life Cycle Analysis (LCA) for that product. Students are then expected to identify possibilities for improvement for both the product and the material, applying an iterative design approach. Students are required to compare the environmental profile of their proposal with existing solutions with an equivalent functionality, to validate the expected environmental benefits of using these recovered materials in their chosen applications.

2.2 Collaboration with local industries

The residues used in the assignments stem from local industry. The collaborating companies provided material to experiment and develop samples, did guided visits to their production facilities and gave feedback at the mid- and final term presentations.

To engage local industries, they are contacted by the course teachers to propose a collaboration. Joint meetings are held, in which examples of previous years' results are shown, after which the company presents a proposal for an innovation project in the field of IDE. The proposal is examined at the institution and based on the length and complexity of the proposal, determines the best format to execute it. All collaborations done for this assignment are framed as an Academic Project, i.e., to be developed as a real-world challenge within a regular academic course. Under this consideration, the parties jointly agree and develop a project brief, which outlines the objectives of the Academic Project and the elements and phases of its development, as well as the composition of the participating teachers and student teams. This document is the base for the collaboration contract to be signed.

Besides the Academic Project, our teaching institution has 3 other formats of collaboration with companies: the Innovation Lab (Part-time, extracurricular engagement, over a period of 8 to 15 weeks), Thesis Projects (engagement of a group of students to develop their final thesis projects with the proposed challenge, for a period ranging between 5 to 8 months) and Industrial Doctorates (research developed by an industrial doctoral student, for a duration of 2-4 years). Intellectual and industrial property rights are agreed on a case-to-case basis.

During the years, this challenge has been presented with the collaboration of four local industries: two manufacturers from the textile sector, one provider of components to the automotive sector and one service-provider for industrial apparel cleaning. Their challenges and materials were all slightly different (summarized and anonymized to be included here):

1. **Waste fluff from industrial washing services.** This waste is made up of fibres that break off from textiles during washing, such as cotton, polyester, and other synthetic materials (image **b** in Figure 1). The fluff is often contaminated with detergents, fabric softeners, and other chemicals used during the washing process, making it challenging to dispose of. The company generates between 250-2500 tons of fluff per day. The aim is to design materials and necessary processes to transform the remaining fluff from industrial laundry filters into useful materials, reducing the environmental impact of the process.

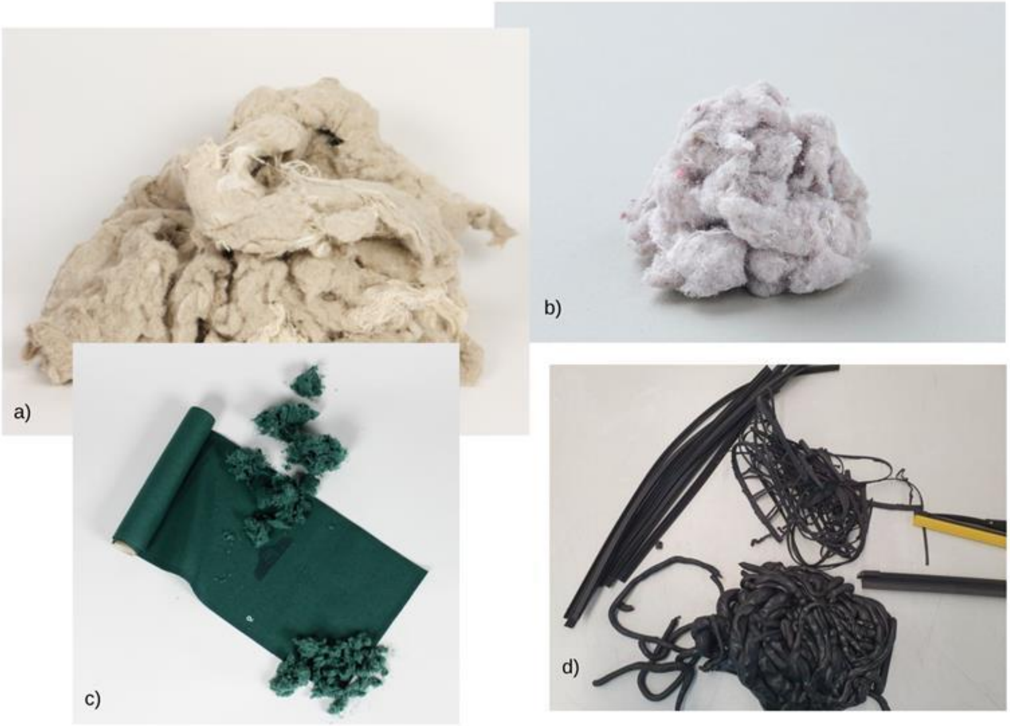

Figure 1. Samples of the waste materials used in the challenge: a) Spinning fibres, b) Laundry fluff, c) Textile cut-offs, and d) Rubber

2. **Waste fibres from a spinning mill.** The spinning mill is specialized in the production of thick yarns of 100% Cotton, 100% Linen, blends of Cotton/Linen, and blends of Cotton/Hemp Open End, with a capacity of 7,000 tons per year. Circa 25 tonnes of waste per year are generated, being the waste composed of fibres, threads, and hemp dust, with small amounts of cotton, released throughout the spinning process (image **a** in Figure 1). These fibres are too short to reuse in the spinning process. The project idea was to demonstrate the possibility of revaluing the organic waste through simple processes and assign possible uses and fields of application to the designed material.
3. **Fabric offcuts from a cotton cloth manufacturer.** Offcuts are the smaller pieces of fabric that are left over after the larger pieces are cut. Often, these offcuts are discarded as waste, contributing to the growing problem of textile waste landfills. The challenge was to explore ways to recycle or repurpose offcuts into new products that can be scalable for industrial production. These specific offcuts were a combination of cotton cloth impregnated with a thermoset polymeric resin and a total of 1 tonne per year are generated (image **c** in Figure 1).
4. **Rubber waste from a windshield wiper manufacturer.** Natural Rubber (NR) is a common material used in windshield wiper blades due to its elasticity and durability. However, the

production and disposal of NR waste can pose environmental challenges. The industrial waste is composed of vulcanized NR bits, followed by chlorinated rubber and, in smaller quantities, non-vulcanized rubber, generating a total of 16,3 tonnes of residue/year (image **d** in Figure 1). Students were asked to look for application areas within the automotive sector.

3 RESULTS

During the first 4 years, a total of 63 student groups (of 3-4 students) participated in this challenge. Of those 63, a selection was made of the projects that obtained high grades in both courses, resulting in 26 projects included in this review. Table 1 gives an overview of the student works included per challenge and how they were assessed. It is important to note that the company that provided the Spinning fibres did not give feedback to student work and during 2019-20, the study only includes the trimester that was not affected by the COVID pandemic.

Table 1. Overview chart of student work and its assessment as defined in section 2

Challenge	Year	# Groups	# Groups Reviewed	Assessed with 12 or more	Company selected	Company Feedback
Laundry fluff	2018-19	20	4	1	3	Yes
Spinning fibres	2019-20	10	5	1	-	No
Spinning fibres	2020-21	13	3	0	-	No
Textile offcuts	2020-21		5	1	3	Yes
Rubber	2021-22	20	9	2	1	Yes
Total	**2018-22**	**63**	**26**	**5**	**7**	**-**

Note that the best assessed works does not always coincide with the projects selected by the companies. In fact, 3 of the 5 projects that were evaluated with 12 points or higher (for the combined criteria of technical viability, material circularity and environmental impact), were selected by the collaborating companies. Of the remaining 2 well evaluated projects, one (with 12/15 points) was the best evaluated in the year when the company did not get involved in the feedback and did not have an interest in taking any of the proposals further, while the other (with 14/15 points) was the best evaluated last year, but the company selected the other well assessed project (with 12/15 points), probably because they worked with a more interesting market application. Each of the remaining four projects selected by the companies obtained a score of 11/15 points. Of all the projects, two have moved on to be further developed in an Innovation Lab collaboration. The following sections describe these best projects in some more detail, indicating next to the project name their corresponding challenge and the assessment score obtained.

3.1 Materials selected by the collaborating industries

- CLINT (Laundry fluff, 14/15) and CUNIU (Textile cut-offs, 13/15), were both selected to be developed further in an Innovation Lab (images **a** and **b** in Figure 2). Both materials contain 99% of the original waste and 1% additive. They use the highest amount of waste of all materials resulting from the challenge, with a simple industrialization process that uses the same manufacturing steps as cardboard, resulting in similar applications (e.g., business cards or packaging).
- PLAXTILE (Laundry fluff, 11/15) is polypropylene reinforced with laundry fluff (image **c** in Figure 2). It increases mechanical strength while the waste results in an interesting aesthetic of the final material, a texture that looks like marble. The manufacturing process is the same as that of current thermoplastics.
- TVÄTT (Laundry fluff, 11/15) only uses waste and gelatine that is a residue of the meat industry. It has interesting aesthetics, with a variety of colours for use in lamp screens in thin layers. In thicker versions, it can be a substitute for plasterboard (image **d** in Figure 2).

Figure 2. Selection of the best materials according to the collaborating industries: a) Clint, b) Cuniu, c) Plaxtile, d)Tvätt, e) Rinew, f) Cotech, and g) Scooter-Roll

- RINEW (Textile cut-offs, 11/15) uses waste from the rice industry mixed with crushed organic cotton waste (image **e** in Figure 2). The manufacturing process is easily scalable for industrial use, with potential applications in fashion industry labels or as material for 3D printing.
- COTECH (Textile cut-offs, 11/15) is a compound made from shredded cotton waste mixed with polycaprolactone (PCL) plastic (image **f** in Figure 2).
- SCOOTER-ROLL (Rubber, 12/15) is made of 50% waste and 50% PUR (polyurethane), which is its weakest point, as the amount of waste reused is only 50% (image **g** in Figure 2). However, it has a high added value application in electric scooter wheels that cannot be punctured given that they have no air chamber.

4 DISCUSSION AND CONCLUSIONS

After four years, of 180 students organized in 63 groups, 26 proposals were deemed interesting and rigorous enough to include in this review. Of those, only two proposed materials were developed further as Innovation Lab projects and were produced in a pilot test. Both materials were mostly composed of the waste provided by the company (99%) and had the support of the collaborating industry to pursue the exploration of the application suggested by the students. So, it seems that a significant factor of success is the interest the industrial partner has in the developed material. This corroborates literature findings that indicate that the main barrier to repurposing industrial waste is the lack of demand for the newly developed material/product [7]. This became evident in cases where the company provided the material and was not providing any feedback.

The challenge as it was presented to the students is quite ambitious, with several students commenting in class that they consider that the assignment is difficult, given that they are expected to develop a competitive material, with an application that added value. Despite the complexity of the challenge, the fact that there have been projects that succeeded in proposing something worthy of further development, speaks in favour of presenting upcycling tasks ambitiously in design education (as proposed by [8]). When the challenge was done with rubber waste, the collaborating company asked students to find applications within the automotive sector, as it would be more relevant to them. This additional requirement had pros and cons: Material applications were developed in greater detail, but with lower motivation and engagement from students. Having the material samples from the beginning of the courses helped students take a hands-on approach to material experimentation and design, making it easier to understand material properties and get actively involved in the challenge.

A commonly applied strategy in the different projects has been to develop hybrid materials, mixing organic and inorganic components. Although the resulting new materials may succeed in valorising existing industrial waste flows, the hybrid materials cannot be considered circular as, at least for now, they are neither recyclable nor compostable. The potential environmental benefits of the materials developed are remarkably influenced by the application defined for them. If used in other applications, these same materials could have higher or similar benefits, or on the contrary, a higher environmental footprint than existing materials. This is part of the learning outcomes that are expected by the course, but it is important to discuss, given that materials obtained from waste per sig are not necessarily more environmentally beneficial than other materials used for specific applications. Likewise, it is also noted that even if the proposals developed use waste materials, they are still expected to perform as well or better than the product they are compared to. This has been commented by designers working with industrial residue, who say that users expect the product to be cheap or suspect that it is of less quality if the product specifically indicates that it contains residue [10].

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