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Material discard reasons: Categorising and characterising industrial waste materials

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Abstract: This paper investigates industrial waste and its characteristics from a design perspective with the objective of assessing why so many materials are discarded. Industrial waste emerges pre-consumer and poses potential as material resources for new product designs on an industrial scale. Most research assesses post-consumer waste, but more than 230 million tons of waste emerge from manufacturing, hence pre-consumer. Current research on industrial waste divides it into scraps and rejects with varying characteristics of predictability and seriality. We add to the research through a two-year research project on designing with industrial waste from Danish manufacturing companies. Through observations, registrations, and semi-structured interviews, we study 24 discarded material cases and assess the challenges for industrial design. From a designer's perspective, we investigate where and why materials are discarded, the categories, and how they can be further characterised. The result is a division of industrial waste into five types: 1) offcuts, 2) rejected materials, 3) rejected objects, 4) process waste, and 5) excess material. They vary in predictability, uniformity, presence of flaws, and data availability. These are characteristics that designers must consider when extending the material lifetime and keeping the material at its integrity level in new product designs.

Introduction

Earth is a limited system, where it is central that we utilise already circulating resources and leave the linear economy of take-make-dispose behind (Ellen MacArthur Foundation, 2013). Similarly, it is essential that we significantly reduce the generation of waste, starting with the production of new products. Numbers from the European Union state that the EU annually generates more than 230 million tons of waste from manufacturing; in Denmark alone, the number is over 1 million tons (Eurostat, 2022). Despite the enormous amounts, waste from manufacturing companies is typically overlooked in discussions of circular economy.

Industrial waste is discarded materials that emerge during the manufacturing of products before they have been in circulation with consumers. (Pacelli et al., 2015) Some material discards, such as the cut-out for a sink when producing a marble kitchen tabletop, cannot be prevented. Others are discarded due to high-quality standards of material surfaces, such as scratches or impurities in an acrylic lamp shade for a designer lamp. Although these material examples are discarded in one manufacturing, they still have a utilisation potential elsewhere. According to the waste hierarchy of prevention – reuse – recycling – recovery – disposal (European Parliament, 2008), the marble material from the kitchen tabletop should be utilised at the highest possible level, reuse, as prevention is not an option. However, the marble is currently granulated down and downcycled into asphalt manufacturing. Ideally, this material could be used in new products where the current size and processing are a quality, as opposed to downcycling and recycling, a standard industry practice (Awogbemi et al., 2022).

When waste materials are recycled, they require significant energy contributions, hence losing the intrinsic economic and environmental value inherent in their composition and shape (Ali et al., 2019). Thus, it is valuable to increase knowledge within this area to support practitioners in transitioning discarded materials into a resource to extend the lifetime of the material before downcycling. However, we lack knowledge of these materials' categories, characteristics, and definitions that emerge pre-consumer.

The research aims to investigate what the industry wastes – and why. The aim is to categorise and characterise discarded materials in manufacturing for two incentives: first, to support designers in using already generated discarded materials in new product designs as a substitute for virgin materials, and second, to outline material characteristics designers must take their origin in to design products that allow a broader inclusion of material "imperfections" in new product designs, hence, to reduce material discard reasons. Thus, this study aims to answer the research question: **What are the categories and characteristics of discarded materials from manufacturing?**

Theory

Extending material lifetime

Much is written about extending the lifetime of products in the use phase and thereby slowing the resource loops, e.g. design for durability, repair, emotional attachment, and second-hand (Haase & Laursen, 2022; Frahm et al., 2024). In comparison, the research on extending material lifetime pre-consumer is limited. While industry and research have examined recycling (Awogbemi et al., 2022; Venkatachalam et al., 2024), the challenge of keeping and utilising discarded materials at their processing stage is an overlooked area. A study by Ali et al. (2019) has found that the economic and environmental advantages of reusing the material rather than recycling point towards a 40% cost saving and 67% saving in energy consumption (Ali et al., 2019).

However, extending the material lifetime of industrial waste is challenging as the discarded materials come in a particular form. The characteristics include small sizes, various shapes and surfaces, and various mechanical and sensorial properties and flaws that vary according to the situation (Feast & Laursen, 2023). This increases the difficulty for the designer as the designer must be able to work with the mistakes in the material that have caused it to become discarded. Still, the material poses value and opportunities to be utilised, which must be understood to design and manufacture with it.

Waste research

Waste research within the circular economy covers areas assessing waste by type, origin, or activities. The term "waste" covers materials, substances, and products, including raw materials, final products, and remnants (Awogbemi et al., 2022). The origin spans from manufacturing at a pre-consumer stage (Pacelli et al., 2015) to post-consumer waste, treating end-of-use/life products as waste (Moalem & Kerndrup, 2023). Literature on waste activities include, among others, the waste hierarchy (European Parliament, 2008) and various R-strategies that extend the hierarchy with more circular strategies (Kirchherr et al., 2017; Potting et al., 2017). Additional activities include zero waste manufacturing (ZWM) on designing products for recycling and reusing post-consumer into manufacturing new products (Kerdlap et al., 2019; Singh et al., 2017), and design for circular production processes through distributed manufacturing, open design, and design for value recovery (Van Dam et al., 2020). Upcycling activities involve upgrading, reusing, repairing, and repurposing products after the use stage but they are currently a niche practice (Caldera et al., 2022).

While most of the literature investigates waste from a post-consumer perspective, the waste treatment pre-consumer is less explored. Studying industrial waste to be utilised with respect to the material's size, form, and processing is found in the mentioned study by Ali et al. (2019), whilst a few other studies supplement by investigating the design process and methods herein when designing with scraps and rejects rather than virgin materials (Feast & Laursen, 2023; Pacelli et al., 2015; Sander et al., 2024). Adding to the research, we dive deeper into the characteristics of industrial waste. We hypothesise that designers must design differently with different types of discarded materials to utilise the already carried out processing and form of the material, thereby respecting the integrity level of the material instead of recycling or downcycling, where the processing and form are lost.

Industrial waste: discarded materials

Pre-consumer waste from the manufacturing industry is defined as manufacturing waste (Awogbemi et al., 2022) or industrial waste (Pacelli et al., 2015). Both terms refer to discarded material resources that are not utilised. Manufacturing waste: *"…consists of any materials left unused or left over after the completion of manufacturing processes."* (Awogbemi et al., 2022, p. 2). Similarly, according to Pacelli et al. (2015): *"Industrial wastes are produced by many manufacturing sectors involving different materials and technologies. Wastes can be defined also as* *the non-value results of a manufacturing process set up to realize specific components."* (Pacelli et al., 2015, p. 79). Despite the term "non-value," current research highlights the potential in discarded materials as value streams rather than waste streams (Moalem & Kerndrup, 2023). Moving forward, we use the term industrial waste.

Industrial waste is divided into two main typologies: scraps and rejects. **Scraps** are exactly predictable waste from manufacturing processes, are directly proportional to designed components, and have some serial and reproducible characteristics. **Rejects** are defective components caused by various factors, which are only statistically predictable and have potentially high variability. (Pacelli et al., 2015) Thus, the characteristics of the waste concern parameters of predictability in amounts and variability in size and shape regarding seriality. Those are important parameters to consider as they emphasise the substantial challenge of using otherwise discarded materials in industrial-scale production compared to new product development processes. (Pacelli et al., 2015)

In upcycling practices, the object is valued for its composition and form (Szaky, 2014). Similarly, industrial waste has built-in value in the composition of the material and the shaping that builds up in the manufacturing process. "Value" is tricky, as it depends on many factors, such as the specific value chain, commercial opportunities, and technological options. Thus, this study simply highlights a shape characteristic when identified.

Method

This study stems from a two-year research project with 20 Danish manufacturing companies that discard materials and thus generate waste (Table 1). The cases have been selected based on collecting a variety of materials to study, being a small/medium-sized company, and having the desire to transform their discarded materials in new products. Each company is matched with a designer, whose task is to 1) understand the discarded material to 2) design new product proposal(s) based on the specific material. Some cases reveal more waste fractions, wherefore this study presents 24 materials. Over approximately two years, we have observed, registered and followed the processes from the first meeting to the presentation of a product proposal.

In this study, we focus on assessing how to categorise and characterise types of discarded materials from an industrial design perspective. With this, the data collection comprises field notes and material registrations from start-up meetings, milestones and final meetings. At the start-up meetings located at the manufacturing companies, we have seen the production, including where and how the waste emerges and what the condition of the material is. Additional semi-structured interviews with each representative from the manufacturing companies were added to the data collection.

The data is analysed through clustering and division of industrial waste into industrial waste categories based on Pacelli et al.'s research (2015). Secondly, the data is analysed to assess the challenges from an industrial design perspective (regarding predictability and variability). Lastly, characteristics and definitions for the categories are synthesised.

#	Material	Description	Discard reason
1	Leather	Irregular pieces of upholstery leather	Scars, imperfections, small sizes
2	Compact laminate	From tabletops	Offcuts from sink or cooking plate
3	Ceramics	From tabletops	Offcuts from sink or cooking plate
4	Metal	Profiled metal sheets for roofs and facing	Scratches an incorrect adjustment of machinery + excess material
5	Wood	From tabletops	Offcuts from sink or cooking plate
6	Textile	Trousers	Wrong colour, wrong size
7	Concrete	Smaller sample of concrete	Testing consistency
8	Wood	Solid wooden floor	Knots, cracks and deviations in shape

9	Acrylic	Full and flat sheet size	Air bubbles and/or scratches
10	Textile	Pieces of various textiles	Small sizes, not fitting with pattern + excess material
11	Metal	Small bits and perforated sheets	Offcuts from punch holes and the punched full sheet
12	Powder coating	Collection of various colours/types	Cleaning pipes in between variant
13	Metal	Oblong pieces, perforated sheets	Offcuts and punched full sheet
14	Cement-bonded wood wool	Baffle plates	Imperfections in surface or broken corners
15	MDF w. veneer	Thin slats with veneer in full length from baffle plates	Broken slats or colour nuance compared to the other slats
16	Felt	Sheets from acoustic panels	Damage on surface after removal of damaged slats
17	Powder coating	Collection of various colours/types	Cleaning pipes in between variants
18	Iron	From tabletops	Offcuts from sink or cooking plate
19	Steel	From tabletops	Offcuts from sink or cooking plate
20	Aluminium	From tabletops	Offcuts from sink or cooking plate
21	PVC	Slimmer rolls of conveyor belts	Adjustment of roll width
22	Rubber	Slimmer rolls of conveyor belts	Adjustment of roll width
23	Aluminium	Smaller sheets with punch-holes	Holes are not centred + excess material
24	Marble	From tabletops	Offcuts from sink or cooking plate

Table 1. Case description of the discarded materials.

Results

Five categories of industrial waste

Table 2 reveals five identified categories of industrial waste: offcuts, rejected materials, rejected objects, process waste, and excess materials (Table 2). The categories emerge at different places in the manufacturing line and for different reasons (Figure 1). The further in the process, the more energy, time, and processing is put into the materials. Excess materials can emerge at more stages, but they will be most utilisation-ready if they emerge at the beginning of manufacturing before the shaping begins.

Industrial waste has a material composition and a shape (Szaky, 2014). Both may be leveraged by designers in new products; however, the composition is easier to utilise in a broad solution field compared to the shape, as it narrows the application areas but increases the intrinsic energy put into the processing.

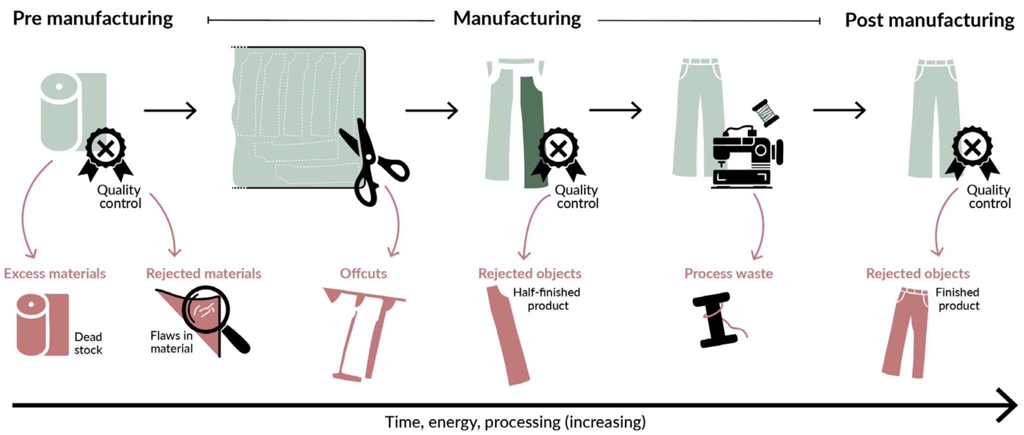

Figure 1. Manufacturing line, generation of discarded materials

#	Material	Scraps/ Offcuts	Rejects		Process waste	Excess materials
			Rejected materials	Rejected objects		
1	Leather	x		x		
2	Compact laminate	x				
3	Ceramics	x				
4	Metal	x		x		x
5	Wood	x				
6	Textile			x		
7	Concrete				x	
8	Wood	x		x		
9	Acrylic		x			
10	Textile	x				x
11	Metal	x				
12	Powder coating				x	
13	Metal	x		x		
14	Cement-bonded wood wool			x		
15	MDF w. veneer			x		
16	Felt			x		
17	Powder coating				x	
18	Iron	x				
19	Steel	x				
20	Aluminium	x				
21	PVC	x				
22	Rubber	x				
23	Aluminium			x		x
24	Marble	x				

Table 2. Where and how in the manufacturing does the discarded materials emerge

Challenges for industrial design

The reasons for discarding the investigated materials vary; small sizes and forms are discarding reasons for offcuts. The rejects are discarded due to various flaws and imperfections in the material or form, typically for aesthetic reasons. The process waste is not rejected because of flaws, but because they are consequences of a manufacturing line. Lastly, excess material is discarded due to purchasing too much material that has become surplus and potentially aesthetically obsolete.

These discard reasons affect the predictability and variability of the materials. Thus, designers face various challenges when designing with discarded materials. The challenges of predictability and variability are assessed case by case (Table 3). These present constraints for the designer to evaluate in the specific cases.

#	Material	Predictability	Variability/uniformity
1	Leather	Medium predictability in quantity, depends on material quality.	Variety in size and shape. 4 flaws: loose skin (around stomach), different structure (at neck spine), scars, and holes.
2	Compact laminate	High predictability in size and shape. Quantity is proportional to production.	Variety in surface according to popularity.
3	Ceramics	See #2	See #2
4	Metal	High predictability in size and shape. Statistical predictable quantity for each colour and profile.	2 types of profiles. 12 colours (80% greyscale, 10% red scale, 10% blue/green/yellow) + excess special colours
5	Wood	High predictability in size and shape. Quantity is proportional to production.	High uniformity, only small natural varieties in the wood.
6	Textile	Low predictability (only statistical) because rejection occurs in quality control.	Always the same form but variety in size or colour.
7	Concrete	High predictability in masses. Proportional to the production.	Variety in roughness, but general uniformity of the consistency for each variant.
8	Wood	Statistical predictability in quantity due to the naturalness of the material.	3 aspects of rejection: knots, cracks, and colour difference.
9	Acrylic	Statistical predictability in quantity, fails in quality control before internal processing.	High uniformity in size and shape but variety in location and number of flaws.
10	Textile	Low predictability on size, shape, type, and amount due to special orders and different markets. Statistical predictability according to orders.	2 types of offcuts: top stitching on textile roll, and offcuts emerging when cutting out the patterns. Additionally excess textile from special colours.
11	Metal	High predictability in amount, proportional with production. Low predictability in size and shape.	High variability in material thickness, sizes, and shapes as they are not sorted (high amounts of each offcut). Variation in offcuts due to adjustment in machinery and design.
12	Powder coating	High predictability in amount. Statistical predictability in colour.	Variety in powder coatings, causing greyscale colour (and quality) mixes.
13	Metal	High predictability in amount. Statistical predictability of rejected objects.	High variety of shapes and sizes of offcuts.
14	Cement-bonded wood wool	Statistical predictable amount.	2 types of flaws: broken corners or imperfections in surface.
15	MDF w. veneer	Statistical predictable amount.	High variety in veneer. 2 types of rejections: damaged surface or colour variety in comparison with surrounding slats.
16	Felt	Low predictability. Depends on rejections of slats (#15)	High uniformity. Different positions of flaws.
17	Powder coating	High predictability in amount. Statistical predictability in colour.	15 colours, 75% grey. Uniformity in mixed colour.
18	Iron	High predictability in size and shape. Quantity is proportional to production.	Uniformity in surface. 4 sizes/shapes.
19	Steel	See #18	See #18
20	Aluminium	See #18	See #18
21	PVC	Highly predictable that offcuts occur, but medium predictability in size of offcuts.	Variety in size and colour.
22	Rubber	See #21	Variety in size.
23	Aluminium	Statistical predictable amount. High predictability in size, shape and surface.	High uniformity.
24	Marble	High predictability in size and shape. Quantity is proportional to production.	High uniformity, variability in surface due to popularity of material and natural variety.

Table 3. Case-specific challenges for industrial design

Characteristics of industrial waste

Summing up the findings, we synthesise the definitions and characteristics of the identified industrial waste categories (Table 4). The characteristics stem from the intrinsic challenges of the cases on predictability and variability/uniformity, including the presence of flaws and data availability observed and discussed in the cases.

Category	Definition	Characteristics
Offcuts	Materials that are cut off in the manufacturing process. *"A good example of this is when we produce kitchen tabletops. This is leftover material [from a sink] that is difficult for us to transform into new tabletops."* (#5)	• Predictable quantity, proportional to production • Context-depended predictability in size and shape • Uniformity in industrial manufacturing (built-in shape) • Variability in manual manufacturing (no specific shape) • No flaws • Data available
Rejected materials	Materials where the rejection occurs pre-manufacturing because they do not meet the quality requirements. *"He has those sunshades on the trucks. And here, they unfortunately have a whole lot that is rejected because it doesn't meet the company's requirements for how it should look."* (#9)	• Not predictable quantity, only statistical • Predictable size • Presence of flaws • Variety in position + type of flaw • Uniform size • Data available
Rejected objects	Materials that have been shaped into a half-finished or finished product that is rejected in manufacturing or post-manufacturing due to e.g. failure in quality control. *"The trousers had been sorted out after production due to issues such as colour differences, stitching, size variations, and similar minor defects."* (#6)	• Not predictable quantity, only statistical • Presence of flaws • Variety in rejection cause • Specific size and shape (built-in shape)
Process waste	Materials that emerge supporting manufacturing processes or tests of materials. "*When we perform quality control of our concrete regarding consistency, we end up with surplus material."* (#7)	• Predictable quantity • Predictable size • Variety in quality (data not available) • Uniformity within a scale • No flaws
Excess material	Materials that are surplus after a manufacturing process/project, often due to special projects and purchase of non-typical colour. *"We encounter situations where something is customer specific. It could be a clinic that orders some chairs in a specific design because they have a certain light pink colour in their clinic, and it must match. So, in those cases, we also have materials that are entirely customer specific."* (#10)	• Predictability depended on special purchases • Variety in quality • Uniform size • No flaws • Data available

Table 4. Categorization of industrial waste and their characteristics

Concluding discussion

Predictability and variability

Scraps/offcuts have been defined by current literature as being "exactly predictable" (Pacelli et al., 2015). However, we have identified two factors influencing predictability and uniformity: 1) manual or industrial manufacturing process and 2) natural or synthetic material (Figure 2).

The generation of leather offcuts (#1, Table 3) is predictable, but the uniformity varies in surface and shape as the manufacturing is manual and the material is natural (lower left corner). Oppositely, compact laminate from the tabletop industry (#2, Table 3) is highly predictable in shape and size as the manufacturing is industrial, and the material's surface is uniform as it is synthetic (upper right corner). The two remaining corners (upper left and lower right) are medium predictable. However, the upper left is categorised as more predictable as it is easier to streamline manufacturing a new product with a variety in surface rather than shape.

Predictability is also identified to cover both 1) size and shape, 2) surface, and 3) amount. Whereas Pacelli et al. (2015) emphasises amount as predictability, we argue that size, shape, and surface must also be assessed for its predictability as a challenge for industrial design, as it restricts the design process.

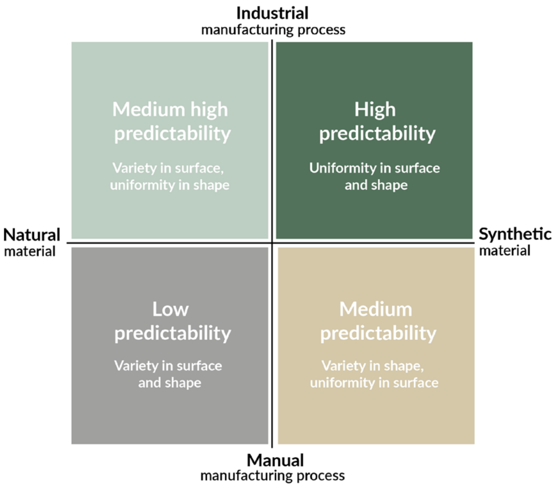

Figure 2. Predictability in offcuts according to material and manufacturing process.

Including discarded materials

Designers face a lot of challenges when including otherwise discarded materials into new product designs due to the predictability, variability, and general characteristics of the materials. They may cause both technical, logistical and aesthetic challenges, which varies according to waste category. Designing new products to include more materials with imperfections rely on the designer’s ability to find solutions that are both viable technically and aesthetically to successfully implement material variability to the market with a design where “imperfections” are read as being on purpose and not as a flaw.

Conclusions

Industrial waste is discarded materials that emerge at a pre-consumer stage and should be used in new product designs instead of being wasted. Designers must consider the challenges and characteristics of discarded materials to design solutions that utilise their intrinsic shape, size, and processing, thereby extending their lifetime. Prior research categorises industrial waste into scraps or rejects, varying in predictability and seriality. Our analysis of 24 discarded materials proposes an extended categorisation into five industrial waste types from a design perspective: 1) offcuts, 2) rejected materials, 3) rejected objects, 4) process waste, and 5) excess materials. These categories vary in predictability, uniformity, flaws, and data availability. Specifically, offcuts' predictability depends on the manufacturing process and material type.

Size, shape, and surface information on the discarded materials reveal challenges to be considered in new design opportunities. Understanding the reasons for discarding is crucial for respecting the already carried out processing and intrinsic value of the material. Utilising the discarded materials may add further processing but should focus on optimising shape and size rather than granulating.

This paper focuses on discarded materials within industrial waste and divides them into categories and characteristics. Implications for further research include assessing the activity of designing with industrial waste, thus investigating how the characteristics are utilised in new designs and how the challenges of including material discards in new product designs are solved. Future studies could explore sectors where material aesthetics are crucial, examining the aesthetic challenges of including imperfections and comparing natural versus synthetic materials.

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