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Combining Flexible and Sustainable Design Principles for Evaluating Designs: Textile Recycling Application

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ABSTRACT

As rates of textile manufacturing and disposal escalate, the ramifications to health and the environment through water pollution, microplastic contaminant concentrations, and greenhouse gas emissions increases. Discarding over 15.4 million tons of textiles each year, the U.S. recycles less than 15%, sending the remainder to landfills and incinerators. Textile reuse is not sufficient to de-escalate the situation; recycling is necessary. Most textile recycling technologies from past decades are expensive,

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create low quality outputs, or are not industry scalable. For viability, textile recycling system designs must evolve with the rapid pace of a dynamic textile and fashion industry. For any design to be sustainable, it must also be flexible to adapt with technological, user, societal, and environmental condition advances. To this end flexible and sustainable design principles were compared: overlapping principles were combined and missing principles were added to create twelve overarching sustainable, flexible design principles (DfSFlex). The Fiber Shredder was designed and built with flexibility and sustainability as its goal and evaluated on how well it met DfSFlex principles. An evaluation of the Fiber Shredder's performance found that increased speed and processing time increases the generation of the desired output - fibers and yarns, manifesting the principles of Design for Separation in design and Facilitate Resource Recovery in processing. The development of this technology, with the application of sustainable and flexible design, fiber-to-fiber recycling using mechanical systems appears promising for maintaining value while repurposing textiles.

Keywords: Design for Manufacturing, Nontraditional Manufacturing Processes, Sustainable Manufacturing

1. INTRODUCTION

In 2015, all United Nations member states adopted the 2030 agenda for sustainable development to put into practice strategies to improve health and education, reduce inequality, spur economic growth, preserve the environment, and decelerate climate change [1]. However, the world is not on track to meet these goals, in part because municipal solid waste (MSW) is still one of the largest contributors to land, water, and air pollution. Every year the United States discards 15.4 million tons of used textile waste into landfills, a vastly overlooked contributor to MSW. In 2018, only 14.7% of all U.S. textiles wasted were recycled, while 18.9% were used for energy recovery and 66.4% were landfilled [2], [3].

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As the world population grows and living standards are raised, demand for a greater variety of textiles also increases. Trends from past decades, such as “fast fashion,” have resulted in consumers discarding clothing items quicker than ever, contributing to a rise in fiber consumption that is significantly impacting the amount of post-industrial and post-consumer fiber waste [4], [5]. The fast fashion business model, defined by mass production, variety, agility, and affordability contributes astronomically to the rate and quantity of trash generation. The majority of textile products have a one-way life cycle: produce, use, and discard as waste that is escalated by the worldwide fast fashion fad, and is unsustainable for the industry and the environment [6], [7].

Processes in the textile industry such as fiber cultivation, petroleum extraction, and textile manufacturing generate a substantial environmental footprint. The increase in energy and water consumption, environmental pollution, extraction of natural resources, and emission of greenhouse gasses raises concerns about the environmental and social sustainability of the textile industry [8]. This industry consumes 53.9 million tonnes of fiber per year and is set to increase 63% by 2030 [9]. The world’s textile industry is the fourth largest contributor to greenhouse gas emissions producing 1.7 million tons of CO_2 each year, accounting for 10% of all global greenhouse gas emissions [10], [11]. Additionally, the industry is responsible for 20% of global clean water pollution and 35% of all microplastics released into the environment [12].

Analysis of the textile industry shows that reuse is more beneficial to the environment than recycling. Although, reuse is not sufficient to reduce textile waste and cannot address the issues surrounding resource scarcity [13], [14]. Since reuse and

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recycling are more sustainable when compared to incineration and landfilling, the production and destruction of textile products must pivot to a circular life cycle, reinforcing a more sustainable economy [4].

The textile recycling sector has great potential to contribute to the circular economy by reducing the production of new textiles from virgin materials, but this sector is still facing several technical challenges [15], [16]. There continues to be few options regarding mechanical recycling for post-consumer textile waste and most of the industrial scale solutions do not yet produce fibers of the same or equal quality and strength that virgin fibers provide [7]. It is important to reinforce that systemic change and technological development are required to enable textile-to-textile recycling [14].

A new approach to designing solutions for the textile waste problem is necessary. Several sustainable design methodologies developed were unsuccessful in addressing the linkages across multiple stages in a product's life cycle [17]; many design methodologies decrease the impacts from specific life cycle stages such as improving production through design for manufacturing and assembly [18], end-of-life through design for disassembly (DfD) [19], design for recyclability [14] and design for adaptability [20] to name a few. Most of these methodologies focus on one product life cycle without considering the continuous evolution of user needs and requirements, the supply chain, environment, economy, and technology. The textile industry sector is constantly reinventing products, materials, processes, machines, and systems. Applying design for sustainability combined with design for flexibility is both what is possible for success and necessary to improve everchanging textile industry systems.

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2. BACKGROUND

A sustainable design aims to reduce consumption of non-renewable resources and minimize waste to limit the negative impacts on the environment and improve the health of society [21]. A flexible design is meant to adapt with growing times, demand, and varying resources. In order to achieve a truly sustainable design, designs must be flexible to avoid obsolescence and becoming waste. One challenge of all recycling systems, including textile recycling, is the variability of input material composition [22], quality [23], volumes [22] and locations. These factors greatly impact the ability of recycling systems to be profitable or to even cover their operational costs [24]. The variables of timing, location, and expense of textiles in need of recycling are constantly changing and greatly impact the designs of recycling systems. It is critical to the success of these recycling systems to create them with the flexibility to adapt with these varying unknowns.

2.1 Design for Flexibility and Design for Sustainability

The 12 Principles of Green Engineering were proposed to provide overall guidance to sustainable design of products, services, and systems and arguably still provide the most widely accepted foundational advice on this topic more than a decade later. These principles promote nonhazardous inputs and outputs, minimal waste, resource efficiency, deconstruction-capable products, lifelong durability, renewable resources, and planning for end of life [25]. However, these design principles do not account for fluctuating environmental conditions, economics, technology advances, and human needs and desires. It is imperative that sustainable design is also created to be flexible to accommodate changing circumstances. Flexibility in design provides room for adjustments to account for a dynamic world with changing necessities and technical objectives [26]. Flexible products, services, and systems are "designed to keep the options open to cope with new operational requirements as they occur [27]." Variable and ever changing circumstances of production and use require flexibility as a key attribute in design for sustainability.

Flexible design can be most simply and universally stated as "an ability to adapt to change [28]." Saleh et al., discusses the need for flexible design to extend the life of products, ideally by decades or more, that incorporate cutting edge technology (e.g. satellite systems and helicopters) [29]. Following the production and implementation of these products, the impacts of these technologies are noticeable in society. User behaviors, desires, and needs evolve with the existence of new technologies. This influences both the design requirements [29] and the environment in which the product operates [27]. Capacity needs may also change over time with new technologies arising creating the need to scale up or down designs to meet demand [27]. In considerations of product design for a circular economy, the demand for a flexible and sustainable design becomes apparent.

Currently, design for sustainability (DfS) has been differentiated from other design methodologies for being applied as a system property instead of a property of individual elements of a system [30]. However, when combined with design for flexibility, design for sustainability improves the flexibility from the system perspective. Therefore, systems

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with Sustainable Flexible Design (DfSFlex) are more likely to thrive in dynamic circular economy models.

Circular material economies demand quality material outputs resulting from end-of-life reuse, remanufacturing, and recycling processes for use in the original manufacturing processes [31]. The dynamic nature of changing product or material inputs and volumes [22], quality [23], and prices [24], [32] for recycling processes create a need for flexibility in systems that aim for sustainability. Specifically for textiles, recycling must consider a wide range of textile products, characterized by product design or end use application, material input, and manufacturing process used. These diversity in initial conditions that create textiles and influence their lifespan are reflected by the diversity in current textile recycling processes [33].

2.2 Current Textile Recycling Processes

Textile recycling can be categorized into three main categories: mechanical, chemical, and biological. Mechanical recycling or fiber recycling is the process in which the fabric is taken apart, preserving the fiber more commonly performed by a shredding or cutting machine. These processes usually require manual intervention to sort the materials and remove notions such as zippers and buttons [9]. Chemical recycling is where the synthetic polymer fibers derived from petrochemicals are depolymerized and the natural or synthetic cellulosic fibers are dissolved. After being disassembled to the molecular-level, the component parts are reprocessed to manufacture new fibers. These processes usually require a mechanical pre-treatment [34]. Biological recycling utilizes enzymes and microorganisms to convert feedstock into different products. The types of

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processes vary according to the fiber material and each material will become a different compound. For example, cotton, hemp or synthetic viscose and rayon fibers are rich in cellulose, a saccharide-based polymer, and could be processed in biorefineries [9], [35].

The recycling routes for chemical, biological and mechanical recycling can be both closed-loop, where recycled outputs are used to manufacture an identical product, or open-loop, where recycled outputs are used in another product manufacturing process [8]. Recycling systems for products and materials are essential to creating circular economies, however many barriers exist to implementation. There is a lack of incentives that motivates consumers to recycle textiles and informational or educational programs only target other types of products [36], [37]. Furthermore, the collection options for textile waste are inefficient and there is an absence of policies and regulations regarding textile recycling [36].

From the material perspective, textile products are complex and heterogeneous, fabrics can be created with different blended materials in different ratios, and sometimes, these materials cannot be submitted to the same recycling process [38]. Additionally, there are several chemicals used in the production of textiles that limits the capabilities of recycling [36].

2.2.1 Mechanical Textile Recycling

Mechanical recycling is well-situated to apply flexible design principles. Mechanical recycling is a scalable and low-cost process that does not require toxic or expensive chemicals used in chemical or biological recycling and can be categorized in different types of processes such as fiber recycling, shredding, thermomechanical recycling, manual extraction, dry processing, thermo-processing and fiber suspension rheology. These processes can be used in closed and open-loop systems depending on the type of the material to be recycled [7], [9], [39].

Among the several mechanical recycling processes, shredding and thermomechanical recycling are the most common. Thermomechanical recycling is the process of melting and extruding synthetic fibers to produce granules used in melt spinning for generating new fibers [39], [40]. In shredding processes, the material has its plastic or metal notions removed so the material can be cut into smaller pieces that are fed into a shredding machine. Inside the machine, the material is usually subjected to an opening process where drums covered radially with coarse spikes pull and tear textiles multiple times until fibers are exposed. From there, the material undergoes a refining process composed of 6-9 drums [39]. The output fibrous material can then be processed again to achieve the desired properties. The shredding process causes a reduction in fiber length, resulting in a decrease of quality and strength when compared to virgin fibers [7].

Even though mechanical recycling is well established in the industry, it is still technologically limited and there is much room for improvement. Different types of machines are available in the market, but few have the flexibility to be used on a wide variety of garments or, if they do, the material output quality is poor. Additionally, none of these machines have been evaluated for performance considering the principles of flexibility and sustainability. As a result, there is a limitation in both standardization and technological advances regarding textile shredding machinery [9], [41], [42].

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2.3 Objective

The purpose of this research is to incorporate flexible design principles into a sustainable design approach to address fluctuating requirements and environments that exist for product and service design. This approach was applied to a fiber-to-fiber mechanical textile recycling system, the Fiber Shredder. The flexible and sustainable design approach was applied to allow maximum variability in both inputs and outputs. The overlapping areas of concern between flexible and sustainable design principles were considered to this aim. An assessment of the flexibility and sustainability aspects in Fiber Shredder's ability to meet the main goal, creating fiber from fiber outputs, was evaluated.

3. MATERIALS AND METHODS

This research proposes a design approach that incorporates flexible design principles into sustainable design while acknowledging the overlaps. An evaluation method for whether a product design successfully incorporates these principles is assessed for a material circular economy application. Specifically, design of a machine that mechanically recycles textiles, i.e., shreds textiles back into fibers, was considered.

3.1 Analytical Approach to Combining Design for Flexibility and Sustainability

Flexible design principles proposed for different applications in the literature (i.e., computer networked servers [43], furniture [28], and wastewater treatment systems [27]) have been compared in Table 1, similar design principles are numbered and colored

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the same across columns. Additionally, these three perspectives on flexible design principles are compared to sustainable design principles designated by the 12 Principles of Green Engineering [25, p. 12]. To this end a proposed combination of the 12 Principles of Green Engineering with Flexible Design principles was made for a total of sixteen principles related to flexible and sustainable design.

Flexible and sustainable design share some principles, and when combined, these methods fill in holes that each method lacks. Design principles that are in underlined or italics are missing in these existing flexible or sustainable design principles respectively. Not all principles across flexibility and sustainability that consider similar concepts are the same, e.g., “Customizable” suggested by Siu and Wong [28] is deemed similar to “Durability Rather than Immortality” from Anastas and Zimmerman [25]. Though these principles are not directly equivalent both ideas aim at extending the life of products up to a point. Where overlap between flexible and sustainable principles may exist, the benefit of the doubt is presumed, and a connection noted. From this perspective, the 12 Principles of Green Engineering are only missing two flexible design principles, but the flexible design principles, despite the generic sustainability principle stated by Siu & Wong [28], are missing seven sustainable design principles. These principles are collated into the following proposed flexible and sustainable design principles (DfSFlex) in Figure 1. Principles that originated from flexible design are italicized and principles from the 12 principles of Green Engineering are bolded, whereas shared principles are both bolded and italicized. The original titles of some principles have been simplified for ease of understanding.

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Originally, the 12 Green Principles of Engineering were stated without any categorization. However, the flexible and sustainable design principles focus on the design, material, and process aspects of products, systems, and services. Thus, each principle was organized into one of these three focus areas, described in more detail below with an example

The design focus reflects changes in products, processes, or systems, henceforth simply called products, which characterize features and functions that these products provide. Within the design focus, flexible design is represented within each of the sustainable design principles by three additional aspects of flexible design were added. For example, the *Integrate Technological Advances* principle reflects design aspects of a product by facilitating updates to existing products after implementation; utilizing modular design is an example of one method that could allow plug-and-play modules that can be switched out for new technologies over time within a product.

The material focus reflects solely sustainable design principles from the 12 Green Principles of Engineering since flexible design principles do not consider or assess material choices' impact specifically. The *Inherently Nonhazardous* principle, shortened from the original name Inherent rather than Circumstantial, reflects the importance of material selection specifically in avoiding materials that may break down into unwanted and potentially harmful byproducts at any product life cycle stage.

The process focus reflects both flexible and sustainable design principles about how the product is handled throughout its life cycle including manufacturing, use, repair and maintenance, and end-of-life stages. For example, the *Facilitate Resource Recovery* principle impacts the processes that will be done to a product – whether that involves part removal, ease of disassembly and remanufacturing, or material separation of components. *Integrate Technological Advances* and *Facilitate Resource Recovery* together represent the originally proposed Design for a Commercial After-Life principle from the 12 Principles of Green Engineering. Table 2 states brief definitions of each principle.

The Green Principles of Engineering have a greater focus on principles to guide the materials chosen during design work than flexible design. The more design and process focused principles both have overlaps and gaps that flexible and sustainable design principles add to each other to improve products throughout their current life cycles and into the next ones.

3.1.1 Evaluation of Design Flexibility and Sustainability Through Principles

Assessing whether product, process, or service designs meet these combined flexible and sustainable design principles can be a way to incorporate design principles to adapt to the rapidly changing climate and socio-technological world. The Fiber Shredder was compared for utilization and manifestation of DfSFlex in its design. Three of the authors assessed the Fiber Shredder on a rating system of 1 = does not meet principle, 3 = possibly meets principles, and 5 = definitely meets principle. The authors, all of whom were intimately familiar with the Fiber Shredder design and had used the machine, met together over two different sessions and each stated their rating in turn. If clarifications on the meaning of the principles were needed, the original source document language was consulted and discussed. After these discussions everyone would rate the criteria. It

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was possible for a rater's understanding of the criteria to change based on clarifications about the meaning of the principles and for someone to update their rating. The average of their three ratings for the Fiber Shredder for each principle was calculated.

3.2 Application: Textile Recycling Design

The flexible and sustainable design principles were developed for use on a specific application - design of a machine to recycle (i.e., shred with drums) discarded textiles into fiber. There were three main outputs for shredding textiles with drums that the recycling process considered in this research: textile pieces, yarns with fibers, and dust. The design considered two main failure mechanics that aided the process of textile shredding by drums wrapped in toothed carding wire, the drum-textile interaction and the tooth-yarn interaction. The drum-textile interaction happens when multiple teeth grab each extremity of the textile fabric sample and stretch it, generating a failure due to tensile forces. Conversely the tooth-yarn interaction, characterized by the interaction of a single tooth with few yarns, generates a failure by shear [44]. Within this analysis, a machine was created to maximize the tooth-yarn interaction by decreasing the distance between drums and modeling the parameters that could affect the process and providing more fiber output such as processing speed and processing time.

The initial prototype of the Fiber Shredder (Figure 2) was composed of two feeding drums moving textiles downward into two shredding drums. The feeding drums were designed with medium-sized carding wires to facilitate textile movement and the shredding drums with small-sized carding wires to concentrate teeth on textiles for

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shredding. Each pair of drums rotates in opposite directions, and while feeding drums rotate at the same speed, the shredding drums had different speeds controlled by a gear system with different ratios and thus radius sizes.

The machine was equipped with motors designed to output 1.56 Nm of torque and vary its rotation frequency from 0-50 Hz (0-3000 rpm). Both the shredding and the feeding system were designed with an axis adjustment mechanism so the distance between drums can be increased or decreased to accommodate the existing variability in thickness of textiles.

The machine was designed with T-Slot aluminum frames to have high modularity. These frames allowed the addition of extra components, improving the adaptability for design optimization. The transmission system was designed to have different gear setups to facilitate the change in mechanical reduction ratio. Additional components were designed to be assembled without needing to disassemble or change the original structure.

After several tests, the problems and concerns were identified, and an action plan was created to improve the system. A set of systems were developed to improve the design without the need of remanufacturing original components, by using the already built-in features to attach these new systems.

The first test with the Fiber Shredder was performed using a 100% cotton knitted material. In this test, the textile put through the shredding process was not completely shredded. The first round of shredded material was fed back into the system until the textile was fully deconstructed into yarns or fibers. This process required the operator to

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feed the material multiple times, which was a problem due to ergonomic concerns and increased processing time. To solve this problem, a barrier was designed and added to the system to keep the material recirculating until it was fully shredded.

After adding the barrier, the system was tested again. This time, fibers attached to the feed drums and clogged the feeding system. To identify if the problem was related to the material, a 100% cotton denim fabric was tested. Due to the high shear and tensile strength of the material, the fabric was not shredded and actuated as a brake, stopping the motors. To solve both problems the feeding rollers were removed, and each motor was assigned to work solely with one of the shredding drums. With this change, the system gained a substantial increase in torque allowing it to successfully shred the 100% cotton denim fabric.

Even though the fabric was shredded, material was getting stuck in between the drums and the machine walls. To solve this problem, a pneumatic system was designed and added to the machine. This pneumatic system pushed the stuck material back towards the drums improving material circulation inside the machine.

The flexibility in design allowed the addition of a drum cover to keep the material recirculating inside the machine and, the features used to attach the feeding system were repurposed for attaching a compressed air system. Both systems allowed the shredded material to have an optimal flux inside the machine, thus increasing the machine`s performance.

Figure 3 shows a section view of the machine with the location of the air nozzles, push-to-open valves, and the drum barrier. After assembling all the components, the

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machine was tested and successfully shredded textiles into fibers and yarns. Parts removed during the optimization stage will be repurposed into other systems supporting nonwoven textile manufacturing research.

3.2.5 Preliminary Analysis of Performance

Several tests were performed to determine the optimal drum speed and processing time to create the largest amount of usable outputs, yarns and fibers. A set of samples were shredded at different relative speeds (S_r) while the other set of samples were shredded for different amounts of time. Equation 1 demonstrates how to calculate the relative speed:

$$S_a - S_b = S_r \tag{1}$$

where S_a is the speed of drum A, S_b is the speed of drum B, and S_r is the relative speed.

For all samples, the air pressure valves were manually activated alternatively every 0.5 seconds. After each sample, the machine was cleaned and inspected to ensure any remaining material was removed and the distance between the drums was calibrated.

Since there are no standards for testing textile mechanical recycling processes, the ASTM D5035-11 [45] and ASTM D1776 [46] were used as a guide to cut and prepare samples prior to the shredding process (Figure 4). The samples were first cut into 209.55x209.55 mm and later divided into six 34.93x209.55 mm strips. The ASTM D5035-11 [45] requires specimens to be cut with their long dimensions parallel to the warp (machine) direction or to the weft (cross) direction. To maintain consistent material properties among all samples, each sample was cut from a single denim roll along the

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same weft and warp angle direction. After marking the cutting perimeter, the textile was cut using a Hercules HRK-100 electric rotating blade textile cutter. The 209.55x209.55mm large square samples were then placed in a temperature and humidity controlled environment for 4 h using a NSRI241WSW/0H chamber following the ASTM D1776 [46].

A single sample was weighed, cut into smaller samples, weighed again to account for any material lost as dust, and then shredded according to each process parameter. The processing time began after the first sample piece was fed into the machine, with an average feeding time of 15s for all samples. Following the shredding, the material was stored in a plastic bag of known mass and weighed again to determine the material loss from shredding, which was characterized as dust.

Each shredded sample went through a manual separation process to separate the textile pieces from yarns and fibers. Any textile pieces that retained any discernible woven structure were characterized as pieces, any yarn or fiber that was separate from a woven structure was characterized as yarn and fiber. Each piece was then weighed to determine the process differences regarding the number of textile pieces, the weight of individual pieces, the average weight of textile pieces, and the overall weight of textile pieces.

To determine the influences of the relative speed between drums on the output recycled material, the primary drum speed was varied while the secondary drum operated with the same speed for every trial. The slower drum operated at a constant speed of 450 rpm while the faster drum speed varied between 900, 1350, and 1800 rpm. The processing time for this test was 30 seconds (Table 3).

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To reveal the impacts of processing time on the output recycled material, the drums' speeds were maintained constant, 1350 rpm for the primary drum and 450 rpm for the secondary drum, and the time varied between 30, 60, and 90 seconds (Table 4).

Following the shredding process, the shredded material was manually sorted into Fibers with Yarns and Unshredded Textile Pieces. The textile pieces and the mixture of fibers and yarns were weighed and compared to the initial sample weight. To measure the amount of process material loss as Dust, equation 1 was utilized:

$$W_{bc} - FY_w - TP_w = D_w \quad (1)$$

where W_{bc} is Weight before cutting, FY_w is Fiber and Yarn weight, TP_w is the Textile Pieces weight and D_w is the Dust weight. The dust weight was considered as the process material loss.

After the samples were characterized into weight percentage, a Goodness-of-fit test was performed for every output of each sample set to identify which set followed normality (p-Value > 0.05). A one-way analysis of variance (ANOVA) was performed for comparing two or more groups [47]. Samples with normal distribution were compared using a Tukey-Kramer HSD test to find if there was a statistically significant difference between these samples. For nonparametric sets, the means were evaluated through a Games-Howell HSD test. These tests only compared pairs with a single different input variable (speed or processing time). The statistical analysis was performed using the software JMP (version Pro 17).

4. RESULTS

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Proposed combined sustainable, flexible design principles were developed, defined, and assessed for effectiveness of their application. An example was utilized to test for the effective application of these principles focusing on textile recycling via the Fiber Shredder. The performance of the Fiber Shredder to meet sustainable, flexible design principles and to recycle discarded textiles into fiber was assessed.

4.1 Flexibility and Sustainability Rating

Table 5 shows the average rating value for the Fiber Shredder design and process based on the DfSFlex principles. A rating of 5 means that the parameter definitely meets that principle and a rating of 1 means that the parameter does not meet the principle. Underlined numbers represent values where all three raters agreed while bold represents values where at least two raters agreed. The closer a value is to 5 amongst all the raters represents agreement that the design or process more than probably implements the sustainability and flexibility design criteria.

The evaluation of the Fiber Shredder design and process resulted in different ratings for all but two principles; considering the design and process separately was important. Regarding the Fiber Shredder design, the three raters only agreed on one principle, *Design for Separation* = 5. For the Fiber Shredder process, the raters agreed on three of the fifteen principles *Inherently Nonhazardous* = 1, *Integrate Material and Energy Flows* = 3, and *Facilitate Resource Recovery* = 5. At least two raters agreed on thirteen ratings when evaluating design and twelve ratings for analyzing the process.

When analyzing the evaluation regarding the Fiber Shredder Design, the agreement among two or more raters tended to be along the line that the Fiber Shredder

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manifested that principle (rating = 5). The only principles where all raters disagreed were *Conserve Complexity*, *Integrate Material and Energy Flows* and *Maximize Efficiency.*

When it comes to evaluating the Fiber Shredder Process, the agreement among two or more raters was split between ratings of 5 and 3 suggesting possible manifestation of the principle. The rating of the following principles suggests slightly higher than possible manifestation within the process of : *Multifunctionality*, *Robust*, *Facilitate Resource Recovery*, *Output-Pull versus Input-Push*, and *Prevent instead of Treat*. The process was evaluated to possibly address that principle (rating = 3) in the following principles: *Conserve Complexity, Design for Separation*, *Minimize Material Diversity*, *Integrate Material and Energy Flows*, and *Maximize Efficiency.* All raters disagreed on the ratings of *Durable Customizability*, *Universality*, and *Renewable Rather than Depleting*.

4.2 Fiber Shredder Recycling Analysis Results

After shredding, the textile pieces produced had different sizes and weights for all samples (Figure 5). During the process, some samples would lay underneath the drums and not be pushed back to the system resulting in completely unshredded pieces, which was only found on the lowest drum speed samples.

Table 6 demonstrates the weights for every step performed according to each sample set where W_{bc} is the weight before cutting, and W_{ac} is the weight after cutting, W_{as} is the weight after shredding.

As shown by Figure 6, samples with relative speed equal to 450 rpm had more textile pieces of which also had a higher average weight. The weights of dust produced

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were similar for samples shredded at 1350 and 1800 rpm while the amount and weight of unshredded textile pieces decreased abruptly for different processing times.

To compare and analyze the samples, a goodness-of-fit test was performed for every output of each sample set with a 95% confidence interval ($p<.05$). The weight percentage for dust, and yarns and fibers had normal distributions while the weight percentage of textile pieces were normal for every sample except samples B ($p=0.0348$) and E ($p<0.0001$).

When analyzing the influence of speed over the recycled material output, higher rotational speeds increased the amount of fibers and yarns and significantly reduced textile pieces by weight by greater than 30% when comparing 450 and 900 rpm and 450 and 1350 rpm (where $p<0.05$ for the pair comparison through Tukey-Kramer HSD test, shown by Figure 7). With the increase in speed there also was a small, but not statistically significant, increase in dust or process losses at less than 1% by weight. The output materials obtained from samples shredded at 1350 and 1800 rpm were very similar, demonstrating that after a certain point, the influence of speed decreases on production efficiency of fibers and yarns. From these investigation parameters, the processing speed of 1350 rpm is recommended for optimal yarn and fiber output while reducing dust production for textile recycling via shredding.

Regarding processing time's influence on the recycled material output, the longer the sample stayed in the process, the more fibers and yarns were produced. At 90 seconds of processing time the material output of textile pieces by weight went to near zero, whereas at 30 seconds over 15% of output was textile pieces. As processing time increases dust production or process losses also increases, although not at a comparable rate to the gains in yarn and fiber. Dust production increased by slightly less than 2% by weight between 30 and 90 seconds of processing time. The gains in usable yarn and fiber output outweigh the small increase in dust production or process loss. From these investigation parameters, the longest processing time considered, 90 seconds, is recommended for optimal yarn and fiber output for textile recycling via shredding (where $p<0.05$ for the comparison of the couples 30s-90s through Games-Howell HSD test).

5. DISCUSSION

The Fiber Shredder was created to be both a flexible and sustainable product that, through unanimous evaluation by three raters, manifested the principles of *Design for Separation* in the machine design and *Facilitate Resource Recovery* in the machine's process. The majority of raters agreed that the Fiber Shredder more than possibly manifested *Integrate Technological Advances, Multifunctionality, Inherently Nonhazardous, Ease of Management, Facilitate Resource Recovery,* and *Prevent instead of Treat* in the machine's design. The majority of raters also agreed that the *Robust, Output-Pull Versus Input-Push*, and *Prevent Instead of Treat* principles were more than possibly manifested in the machine's process.

The T-slot aluminum structure of the Fiber Shredder, which can easily be disassembled and added to, allowed the design to meet the *Design for Separation* criteria. The design utilized standard components (i.e., bolts, nuts, gears, variable frequency drives), which allowed easy disassembly, reconfiguration, repair, and replacement within the design. Using standard components does not require manufacturing new tools to for

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production or maintenance, which shows that the Fiber Shredder design more than possibly manifests the principles *Integrate Technological Advances, Multifunctionality*, *Ease of Management,* and *Facilitate Resource Recovery*.

The ability to shred different material types was evaluated in an initial test where the machine successfully shredded different fabric materials such as knitted polyester, cotton, cotton-polyester blends, and cotton-elastane blends and woven cotton-polyester blends, silk, rayon, and nylon, making it a *universal* product. These materials were tested without following a standard operating procedure; in the future, a systematic study will be performed to evaluate the shredding performance over a variety of materials. Since only discarded materials are processed in the machine, no new resources are needed thereby satisfying both goals of *Renewable Rather than Depleting* and *Facilitates Resource Recovery*. *Output-Pull versus Input-Push, Prevent Instead of Treat*, and the *Robust* principles were more than possibly manifested by the ability to shred a variety of textile materials to keep up with the fashion industry's many varieties of textile material used.

The *Conserve Complexity* principle was not fully met. While it was rated that most components could be disassembled or upgraded, other components must undergo modifications when scaling up the design. It was argued that the *Integrate Material and Energy Flows* principle was not met due to the use of electricity and pressurized energy sources even if this is standard in conventional factories. It was decided that *Maximum Efficiency* could be better fully achieved with a higher volume production capability and increased automation. While the Fiber Shredder is a new technology, it has the possibility

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of being improved to work for other industries such as in thermal and acoustic insulation, civil construction, etc. to satisfy the *Durable Compatibility* criteria. The machine can currently shred a variety of textile materials but has yet to be tested with non-textile materials to fully satisfy *Universality*. Though the machine reduces waste by utilizing used textiles, it is still powered by electricity which resulted in not completely meeting the requirements for the *Renewable Rather than Depleting* principle.

To better meet these design goals, processing parameters were adjusted until the optimal outcomes were achieved at faster shredding drum processing speeds of greater than 1350 rpm and at least 90 seconds for processing durations. By following the optimizations parameters, the Fiber Shredder better exemplifies each design principle to create a more flexible and sustainable machine. These processing parameters stood out as aiding the creation of the desired output yarns and fibers without significantly increasing dust production supporting the theory presented by Alves et. al [44] that increasing drum speed increases fibers and yarns and decreases textile pieces generated. This fills a key gap in the academic literature documenting and discussing the means of manufacturing recycled fibers rather than the utilization of recycled fibers in textile production [48]–[51].

The lack of published studies regarding textile recycling machines made comparing performance difficult between the Fiber Shredder and other technologies. Samples provided by collaborators using Cornell University's Fiberizer (a lab scale shredder) [52] and the Franklin Miller Taskmaster® Model TM8512 textile shredder (industrial scale) [53] have shown these machines capable of shredding a variety of textiles into textile pieces and some yarns but not achieving many fibers. Taskmaster® shredding machines are suitable for a range of different applications such as shredding bottles, cans, waste, and textiles, while the Fiberizer only handles textiles. Both machines do not have features to control the speed or distance between the cutting tools. Additionally, these specific machines lack modularity in design that might allow for improvement of shredding capabilities for specific applications. Therefore, the Fiberizer and Taskmaster® TM8512 are considered to be less *Flexible* since neither the input parameters nor design can be changed to address different types of textiles. Even though the Taskmaster® TM8512 demonstrates *Universality* in shredding different types of materials other than textiles, this shredder does not produce usable fibers decreasing the utility and thus *Universality* of the output material.

Further improvement in this design could include modifications to better *Integrate Technological Advances* and *Integrate Material and Energy Flows* to negate the need for any new materials, such as bonding agents and virgin fibers, and allow the machine to be adjusted over time as new technologies are introduced and user needs change. Finally, testing and mitigation of any possible microplastic contamination produced from synthetic textile shredding should be performed to adhere to the *Inherently Nonhazardous* Principle.

The Fiber Shredder was designed to fit within existing textile recycling systems with their large volumes of varying material content, quality, and location. The Fiber Shredder is portable operating on top of a small car that can fit in the back of a small truck or SUV allowing easy transport of the device to where large volumes of discarded textiles

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are located. The variety of textiles including natural plant-based (cotton), natural animal proteins (silk), synthetic, and natural-synthetic blends that the Fiber Shredder can recycle back into yarns and fibers suggests an ease in handling varied material content and quality. The next step for a second prototype involves scaling up the model size to meet the volume demand from textiles in need of repurposing. The flexibility of the Fiber Shredder design and process allows for meeting the challenges posed by textile recycling system unknowns.

6. CONCLUSION

A combined flexible and sustainable design approach (DfSFlex) was proposed based on existing flexible sustainable design principles. A mechanical textile recycling system was designed, built, and tested with the goal of creating a machine embodying these key principles. This machine, the Fiber Shredder, excelled at end-of-life processes by supporting material recovery and reuse. Multiple tests were performed to gauge optimal performance parameters including processing speed and processing time. The results indicated that at faster speeds and longer processing time, increased amounts of yarns and fibers were outputted with a minimal increase in dust production, thus satisfying the *Design for Separation* and *Facilitates Resource Recovery* principles. This application of DfSFlex principles demonstrates that considering both sustainability and flexibility principles in designs promotes more well-rounded and circular products and processing systems to protect and adapt with users and the environment.

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NOMENCLATURE

MSW	Municipal solid Waste
DfD	Design for Disassembly
DfS	Design for Sustainability
DfSFlex	Design for Sustainability and Flexibility
g	Grams
Nm	Newton meter
Hz	Hertz
rpm	Rotations per minute
PSI	Pound per square inch
MPa	Mega Pascal
S_a	Speed of drum A
S_b	Speed of drum B
S_r	Relative speed
Rh%	Relative Humidity

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°C	Degrees Celsius
s	Seconds
W_{bc}	Weight before cutting
W_{ac}	Weight after cutting
W_{as}	Weight after shredding
TP_w	Textile Pieces weight
FY_w	Fibers and Yarns weight
D_w	Dust weight

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REFERENCES

[1] United Nations General Assembly Economic and Social Council, "SDG Progress Report," United Nations, New York, New York, A/78/50, 2023. Accessed: Jun. 22, 2023. [Online]. Available: https://sdgs.un.org/sites/default/files/2023-04/SDG_Progress_Report_Special_Edition_2023_ADVANCE_UNEDITED_VERSION.pdf

[2] U.S. Environmental Protection Agency (EPA), "What are the trends in wastes and their effects on human health and the environment?," U.S. Environmental Protection Agency (EPA), Mar. 2023. Accessed: Jun. 30, 2023. [Online]. Available: https://www.epa.gov/report-environment/wastes

[3] U.S. Environmental Protection Agency (EPA), "Advancing Sustainable Materials Management: Facts and Figures Report," Apr. 2023. Accessed: Jun. 22, 2023. [Online]. Available: https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/advancing-sustainable-materials-management

[4] J. P. Juanga-Labayen, I. V. Labayen, and Q. Yuan, "A Review on Textile Recycling Practices and Challenges," *Textiles*, vol. 2, no. 1, pp. 174–188, Mar. 2022, doi: 10.3390/textiles2010010.

[5] Y. Wang, "Fiber and Textile Waste Utilization," *Waste Biomass Valorization*, vol. 1, no. 1, pp. 135–143, 2010, doi: 10.1007/s12649-009-9005-y.

[6] L. Navone, K. Moffitt, K.-A. Hansen, J. Blinco, A. Payne, and R. Speight, "Closing the textile loop: Enzymatic fibre separation and recycling of wool/polyester fabric blends," *Waste Manag.*, vol. 102, pp. 149–160, Feb. 2020, doi: 10.1016/j.wasman.2019.10.026.

[7] D. Damayanti, L. A. Wulandari, A. Bagaskoro, A. Rianjanu, and H.-S. Wu, "Possibility Routes for Textile Recycling Technology," *Polymers*, vol. 13, no. 21, p. 3834, Nov. 2021, doi: 10.3390/polym13213834.

[8] K. Shirvanimoghaddam, B. Motamed, S. Ramakrishna, and M. Naebe, "Death by waste: Fashion and textile circular economy case," *Sci. Total Environ.*, vol. 718, p. 137317, May 2020, doi: 10.1016/j.scitotenv.2020.137317.

[9] M. Ribul, A. Lanot, C. Tommencioni Pisapia, P. Purnell, S. J. McQueen-Mason, and S. Baurley, "Mechanical, chemical, biological: Moving towards closed-loop bio-based recycling in a circular economy of sustainable textiles," *J. Clean. Prod.*, vol. 326, p. 129325, Dec. 2021, doi: 10.1016/j.jclepro.2021.129325.

[10] D. Oettli, "WWF Apparel and Textiles Industry Report," World Wildlife Federation (WWF), Switzerland, 2023. Accessed: Jun. 30, 2023. [Online]. Available: https://www.wwf.ch/fr/nos-objectifs/rapport-du-wwf-sur-lindustrie-de-lhabillement-et-des-textiles

[11] ClimateSeed, "Textile industry: environmental impact and regulations," Sep. 28, 2022. https://climateseed.com/blog/secteur-du-textile-impact-environnemental-et-r%C3%A9glementation (accessed Jun. 30, 2023).

[12] European Parliament, "The impact of textile production and waste on the environment (infographic) | News | European Parliament," Dec. 29, 2020. https://www.europarl.europa.eu/news/en/headlines/society/20201208STO93327/the-impact-of-textile-production-and-waste-on-the-environment-infographic (accessed Oct. 09, 2022).

[13] D. Watson *et al.*, *EPR-systems and new business models*. Copenhagen: Nordisk

Ministerråd, 2015. Accessed: Jun. 22, 2023. [Online]. Available: http://norden.diva-portal.org/smash/get/diva2:791018/FULLTEXT02.pdf
[14] I. M. Sandvik and W. Stubbs, "Circular fashion supply chain through textile-to-textile recycling," *J. Fash. Mark. Manag. Int. J.*, vol. 23, no. 3, pp. 366–381, Jan. 2019, doi: 10.1108/JFMM-04-2018-0058.
[15] J. Baruque-Ramos, M. C. Amaral, M. C. Laktim, H. N. Santos, F. B. Araujo, and W. F. Zonatti, "Social and economic importance of textile reuse and recycling in Brazil," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 254, p. 192003, Oct. 2017, doi: 10.1088/1757-899X/254/19/192003.
[16] W. Leal Filho *et al.*, "A review of the socio-economic advantages of textile recycling," *J. Clean. Prod.*, vol. 218, pp. 10–20, May 2019, doi: 10.1016/j.jclepro.2019.01.210.
[17] M.-C. Chiu and C.-H. Chu, "Review of sustainable product design from life cycle perspectives," *Int. J. Precis. Eng. Manuf.*, vol. 13, no. 7, pp. 1259–1272, Jul. 2012, doi: 10.1007/s12541-012-0169-1.
[18] G. Boothroyd, P. Dewhurst, and W. A. Knight, *Product design for manufacture and assembly*. Boca Raton, Florida: CRC press, 2010.
[19] University of the Arts London, United Kingdom and L. Forst, "Textile thinking in practice: Creative textile design methods as research in a circular economy," presented at the DRS2022: Bilbao, Jun. 2022. doi: 10.21606/drs.2022.527.
[20] M. E. Kasarda *et al.*, "Design for adaptability (DFAD)—a new concept for achieving sustainable design," *Robot. Comput.-Integr. Manuf.*, vol. 23, no. 6, pp. 727–734, Dec. 2007, doi: 10.1016/j.rcim.2007.02.004.
[21] U.S. General Services Administration, "Sustainable Design," Mar. 17, 2021. https://www.gsa.gov/real-estate/design-and-construction/sustainability/sustainable-design#:~:text=Sustainable%20design%20seeks%20to%20reduce,and%20create%20healthy%2C%20productive%20environments (accessed Jul. 27, 2023).
[22] M. J. Realff, M. Raymond, and J. C. Ammons, "E-waste: An opportunity," *Mater. Today*, vol. 7, no. 1, pp. 40–45, Jan. 2004, doi: 10.1016/S1369-7021(04)00054-9.
[23] C. Roithner and H. Rechberger, "Implementing the dimension of quality into the conventional quantitative definition of recycling rates," *Waste Manag.*, vol. 105, pp. 586–593, Mar. 2020, doi: 10.1016/j.wasman.2020.02.034.
[24] E. McCauley and I. Jestratijevic, "Exploring the Business Case for Textile-to-Textile Recycling Using Post-Consumer Waste in the US: Challenges and Opportunities," *Sustainability*, vol. 15, no. 2, Art. no. 2, Jan. 2023, doi: 10.3390/su15021473.
[25] P. T. Anastas and J. B. Zimmerman, "Design through the 12 principles of green engineering," *Environ. Sci. Technol.*, vol. 37, no. 5, pp. 94A-101A, 2003.
[26] P. K. Palani Rajan, M. Van Wie, M. I. Campbell, K. L. Wood, and K. N. Otto, "An empirical foundation for product flexibility," *Des. Stud.*, vol. 26, no. 4, pp. 405–438, Jul. 2005, doi: 10.1016/j.destud.2004.09.007.
[27] M. Spiller, J. H. G. Vreeburg, I. Leusbrock, and G. Zeeman, "Flexible design in water and wastewater engineering – Definitions, literature and decision guide," *J. Environ. Manage.*, vol. 149, pp. 271–281, Feb. 2015, doi: 10.1016/j.jenvman.2014.09.031.
[28] K. W. M. Siu and K. S. L. Wong, "Flexible design principles: Street furniture

design for transforming environments, diverse users, changing needs and dynamic interactions," *Facilities*, vol. 33, no. 9/10, pp. 588–621, Jan. 2015, doi: 10.1108/F-02-2014-0021.

[29] J. H. Saleh, D. E. Hastings, and D. J. Newman, "Flexibility in system design and implications for aerospace systems," *Acta Astronaut.*, vol. 53, no. 12, pp. 927–944, Dec. 2003, doi: 10.1016/S0094-5765(02)00241-2.

[30] F. Ceschin and I. Gaziulusoy, "Evolution of design for sustainability: From product design to design for system innovations and transitions," *Des. Stud.*, vol. 47, pp. 118–163, Nov. 2016, doi: 10.1016/j.destud.2016.09.002.

[31] J. Kirchherr, D. Reike, and M. Hekkert, "Conceptualizing the circular economy: An analysis of 114 definitions," *Resour. Conserv. Recycl.*, vol. 127, pp. 221–232, Dec. 2017, doi: 10.1016/j.resconrec.2017.09.005.

[32] P. Stromberg, "Market imperfections in recycling markets: conceptual issues and empirical study of price volatility in plastics," *Resour. Conserv. Recycl.*, vol. 41, no. 4, pp. 339–364, Jul. 2004, doi: 10.1016/j.resconrec.2004.02.002.

[33] B. Piribauer and A. Bartl, "Textile recycling processes, state of the art and current developments: A mini review," *Waste Manag. Res. J. Sustain. Circ. Econ.*, vol. 37, no. 2, pp. 112–119, Feb. 2019, doi: 10.1177/0734242X18819277.

[34] G. Sandin and G. M. Peters, "Environmental impact of textile reuse and recycling – A review," *J. Clean. Prod.*, vol. 184, pp. 353–365, 2018, doi: 10.1016/j.jclepro.2018.02.266.

[35] I. K. M. Yu *et al.*, "Chemicals from lignocellulosic biomass: A critical comparison between biochemical, microwave and thermochemical conversion methods," *Crit. Rev. Environ. Sci. Technol.*, vol. 51, no. 14, pp. 1479–1532, Jul. 2021, doi: 10.1080/10643389.2020.1753632.

[36] G. Hole and A. S. Hole, "Improving recycling of textiles based on lessons from policies for other recyclable materials: A minireview," *Sustain. Prod. Consum.*, vol. 23, pp. 42–51, Jul. 2020, doi: 10.1016/j.spc.2020.04.005.

[37] N. Thompson, "Textile Waste & The 3R's: Textile waste strategy recommendations for the City of Toronto," York University, 2017.

[38] E. Karell and K. Niinimäki, "Addressing the Dialogue between Design, Sorting and Recycling in a Circular Economy," *Des. J.*, vol. 22, no. sup1, pp. 997–1013, Apr. 2019, doi: 10.1080/14606925.2019.1595413.

[39] S. Roos *et al.*, "White paper on textile recycling," Mistra Future Fashion, Stockholm, Sweden, 2019:09, 2019. Accessed: Jun. 23, 2023. [Online]. Available: http://rgdoi.net/10.13140/RG.2.2.31018.77766

[40] D. G. K. Dissanayake and D. U. Weerasinghe, "Fabric Waste Recycling: a Systematic Review of Methods, Applications, and Challenges," *Mater. Circ. Econ.*, vol. 3, no. 1, p. 24, Dec. 2021, doi: 10.1007/s42824-021-00042-2.

[41] N. Pensupa, "Recycling of end-of-life clothes," in *Sustainable Technologies for Fashion and Textiles*, Elsevier, 2020, pp. 251–309. doi: 10.1016/B978-0-08-102867-4.00012-8.

[42] P. Athanasopoulos and A. Zabaniotou, "Post-consumer textile thermochemical recycling to fuels and biocarbon: A critical review," *Sci. Total Environ.*, vol. 834, p. 155387, Aug. 2022, doi: 10.1016/j.scitotenv.2022.155387.

[43] S. Andradóttir, H. Ayhan, and D. G. Down, "Design Principles for Flexible

Systems," *Prod. Oper. Manag.*, vol. 22, no. 5, pp. 1144–1156, 2013, doi: 10.1111/poms.12009.

[44] P. H. T. F. Alves, A. R. Clarke-Sather, S. Carlson, and A. Martini, "Theoretical Method for Characterizing Textile Failure Mechanics in Mechanical Recycling with Carded Drums," in *ASME 2023 18th International Manufacturing Science and Engineering Conference*, Rutgers University, New Brunswick, NJ, 12-16 2023.

[45] ASTM. "D5035 Standard Test Method for Breaking Force and Elongation of Textile Fabrics (Strip Method)." Annual Book of ASTM Standards 7. doi: 10.1520/D5035-11R19.

[46] ASTM "D1776 Practice for Conditioning and Testing Textiles," ASTM International. doi: 10.1520/D1776_D1776M-16.

[47] A. Ross, *Basic and advanced statistical tests writing results sections and creating tables and figures*, 3rd edition. Rotterdam: Sense Publishers, 2018.

[48] N. P. Tran, C. Gunasekara, D. W. Law, S. Houshyar, S. Setunge, and A. Cwirzen, "Comprehensive review on sustainable fiber reinforced concrete incorporating recycled textile waste," *J. Sustain. Cem.-Based Mater.*, vol. 11, no. 1, pp. 28–42, Jan. 2022, doi: 10.1080/21650373.2021.1875273.

[49] Environmental & Occupational Health Assessment Program, "Insulation And Your Home: Health Considerations." Sep. 2014. Accessed: Jun. 30, 2023. [Online]. Available: https://portal.ct.gov/-/media/Departments-and-Agencies/DPH/dph/environmental_health/eoha/pdf/InsulationFS12014Revpdf.pdf

[50] C. Stall-Meadows and G. Peek, "Recycled Household Textiles and Clothing," 2009. Accessed: Jun. 26, 2023. [Online]. Available: https://shareok.org/bitstream/handle/11244/334863/oksa_T-4318_2009-03.pdf?sequence=1

[51] M. Kimm, N. Gerstein, P. Schmitz, M. Simons, and T. Gries, "On the separation and recycling behaviour of textile reinforced concrete: an experimental study," *Mater. Struct.*, vol. 51, no. 5, p. 122, Oct. 2018, doi: 10.1617/s11527-018-1249-1.

[52] Franklin Miller, "Shredders." Livingston, New Jersey, 2022. Accessed: Oct. 03, 2023. [Online]. Available: https://franklinmiller.com/shredders/

[53] S. D'Angelo, "Team develops machine with aim of ending textile waste," *Cornell Chronicle*, Ithaca, New York, Apr. 19, 2017. Accessed: Oct. 03, 2023. [Online]. Available: https://news.cornell.edu/stories/2017/04/team-develops-machine-aim-ending-textile-waste

Figure Captions List

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Fig. 3 Fiber Shredder improvements including (a) air nozzles and push valve to operate and (b) drum cover

Fig. 4 Sample preparation methodology

Fig. 5 Examples of material output obtained from textile shredding process: a) Textile Pieces b) Fibers with yarns

Fig. 6 Influence of speed and processing time on shredded output.

Fig. 7 Statistical analysis of sample outputs.

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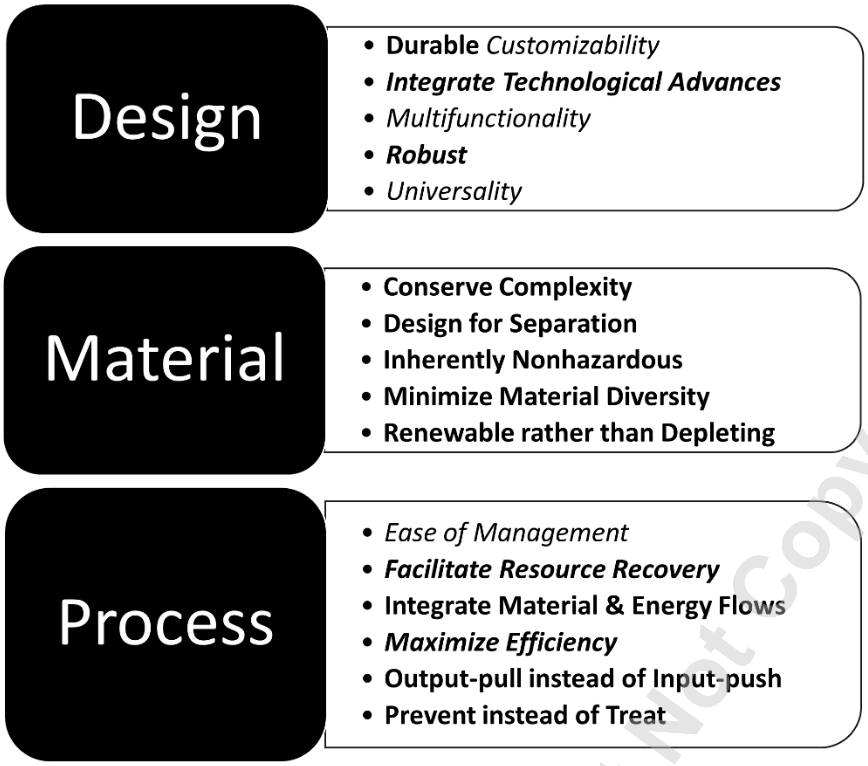

Figure 1: Proposed Sustainability (in bold) and Flexible (in *italics*) Design Principles (shared principles are bolded and *italicized*).

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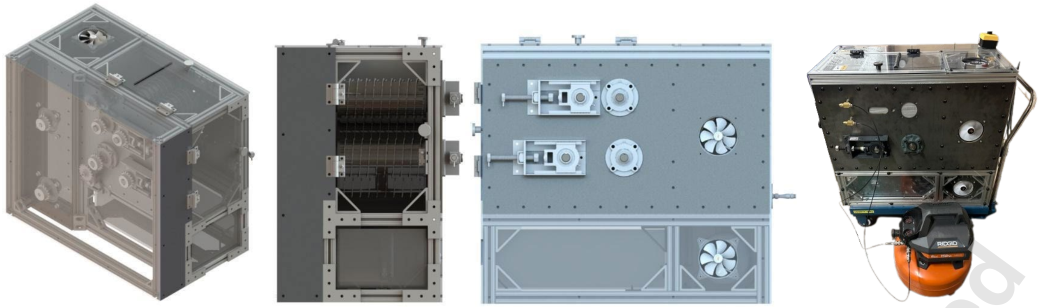

Figure 2: Fiber Shredder isometric, side, and back views, and machine setup with air-compressor.

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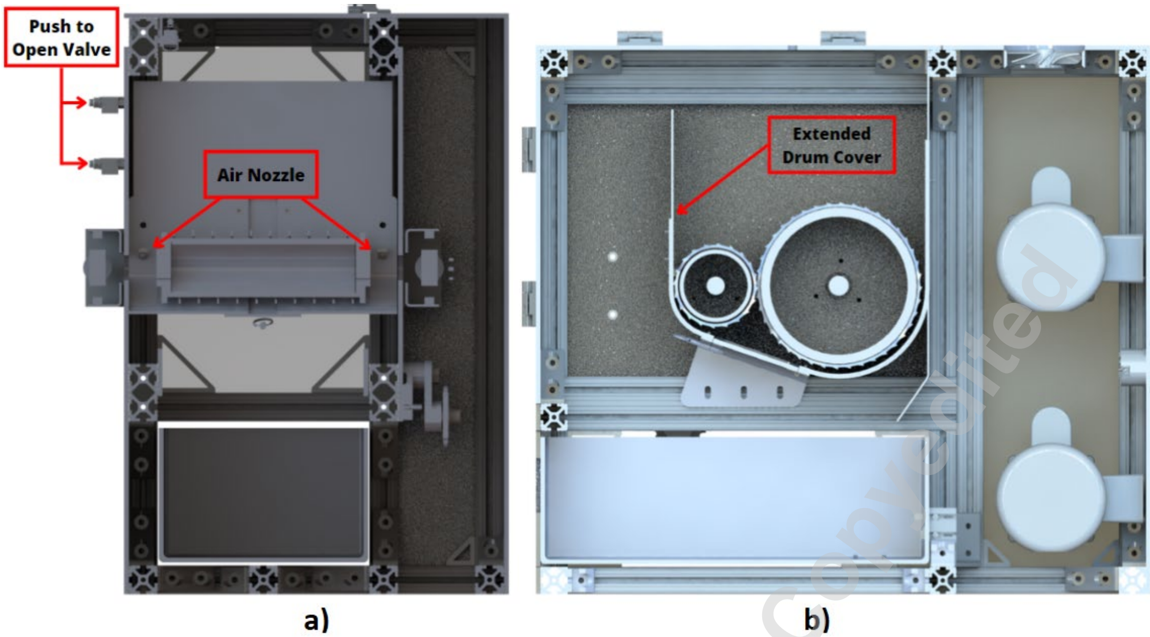

Figure 3: Fiber Shredder improvements including (a) air nozzles and push valve to operate and (b) drum cover

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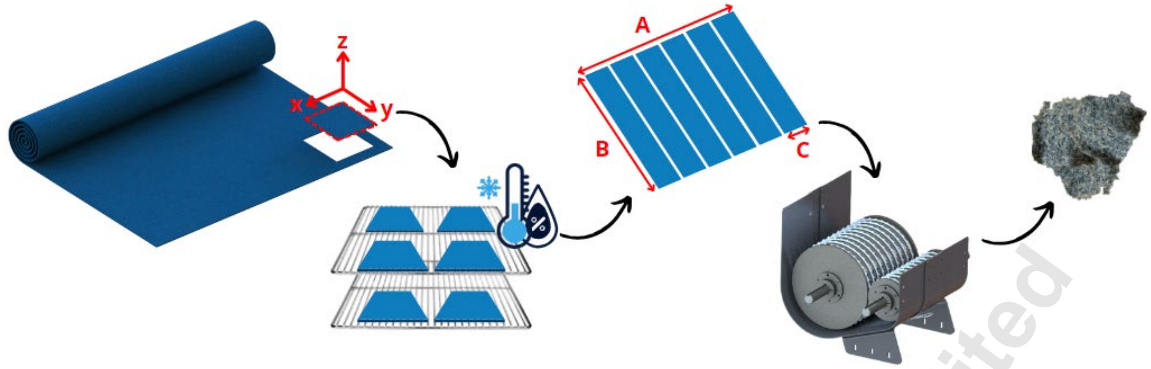

Figure 4: Sample preparation methodology

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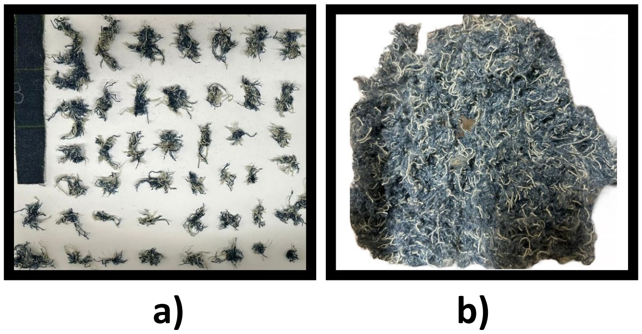

Figure 5: Examples of material output obtained from textile shredding process: a) Textile Pieces b) Fibers with yarns

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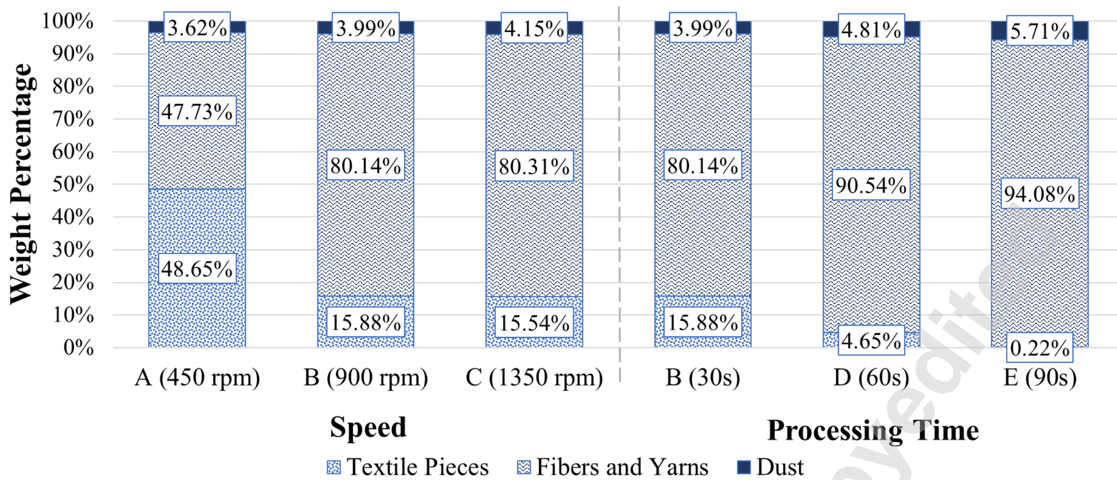

Figure 6: Influence of speed and processing time on shredded output.

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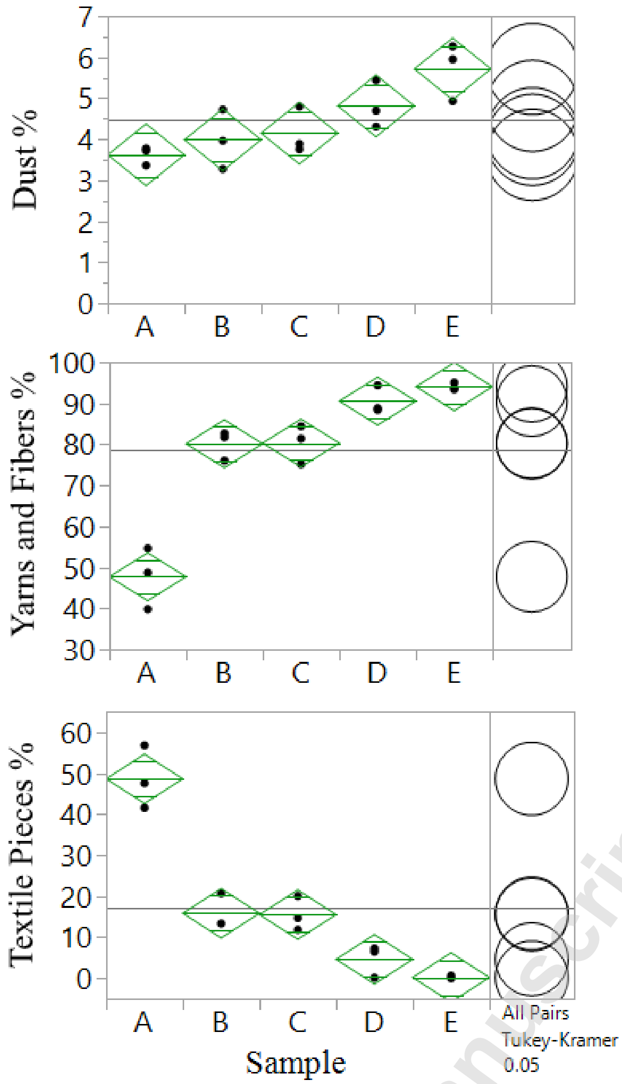

Figure 7: Statistical analysis of sample outputs.

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Table Caption List

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Table 1: Comparison of flexible and sustainable design principles

Flexible Design Principles			12 Principles of Green Engineering
Andradottir, Ayha, & Down	Siu & Wong	Spiller et al.	Anastas & Zimmerman
3- Robust (Adapts to changes in demand and performance) ***5- Trained for all Tasks*** **9- Efficient (Maximizes capacity)**	**1- Customizable** *2- Multifunctional* **3- Responsive to Changing Circumstances** *4- Easy & Convenient Management (Ease of Management)* ***5- Universality*** **7- Sustainability**	**3- Robust (Adapts to changes in demand, performance, capacity)** **7- Facilitates Resource Recovery** **8-Integrates Technological Advances**	**1- Durability Rather Than Immortality** **3- Meet Need, Minimize Excess** 6- Conserve Complexity **7& 8- Design for Commercial "Afterlife"** **9 - Maximize Efficiency** 10- Output-Pulled vs Input-Pushed 11- Minimize Material Diversity 12- Integrate Material and Energy Flows 13- Renewable Rather Than Depleting 14- Inherent Rather Than Circumstantial 15- Prevention Instead of Treatment 16- Design for Separation

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Table 2: Brief definition of sustainable (bold) and flexible (in *italics)* design principles (shared principles are bolded and italicized).

Principle	Definition	Source
Durable *Customizability*	Design products for a goal lifetime, and no longer, so that the products can still be altered to fit their situations specifically	[25], [28]
Integrate Technological Advances	Design products to incorporate innovations over time and use	[27]
Multifunctionality	Design products to organize multiple functions by bundling by similarity, reduce steps needed for achievement, and/or divide into modules	[28]
Robust	Design products to meet requirements under changes to demand, capacity, performance, circumstances, and the environment	[25], [27], [28], [43]
Universality	Design products to complete diverse tasks given a wide range of abilities, needs, and communication modes	[28], [43]
Conserve Complexity	Select materials to maintain embodied energy, processing, and information throughout the product life cycle and beyond	[25]
Design for Separation	Embed distinct materials for easy removal by type to facilitate end of life material recovery	[25]
Inherently Nonhazardous	Select materials that avoid unwanted and potentially harmful byproducts at any product life cycle stage	[25]
Minimize Material Diversity	Select the least number of materials that provide needed product performance to facilitate end of life material recovery	[25]
Renewable rather than Depleting	Select material and energy inputs and rates of use that are inexhaustible and replenishable	[25]
Ease of Management	Facilitate these processes; repair, replacement, transport, storage, and routine maintenance	[28]
Facilitate Resource Recovery	Accommodate processes that repurpose, recycle, and remanufacture value through product materials and components	[25], [27], [28]
Integrate Material and Energy Flows	Create life cycle processes that utilize existing material and energy movement already present instead of adding new sources	[25]
Maximize Efficiency	Create processes that utilize mass, energy, space, and time effectively, fully, and systematically especially under changing circumstances	[25], [43]

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Output-pulled instead of Input-pushed	Develop processes that satisfy existing and changing demand	[25]
Prevent instead of Treat	Innovate and utilize zero waste processes that avert the need for waste handling	[25]

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Table 3: Sample parameters for speed comparison

Sample	Material	n	S_a (rpm)	S_b (rpm)	S_r (rpm)	Time (s)
A	Denim	3	900	450	450	30
B	Denim	3	1350	450	900	30
C	Denim	3	1800	450	1350	30

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Table 4: Sample parameters for processing time comparison

Sample	Material	n	S_a (rpm)	S_b (rpm)	S_r (rpm)	Time (s)
B	Denim	3	1350	450	900	30
D	Denim	3	1350	450	900	60
E	Denim	3	1350	450	900	90

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Table 5: DfSFlex principles evaluated for manifestation in Fiber Shredder design

Flexible Sustainable Design		Fiber Shredder Design	Fiber Shredder Process
Design	Durable *Customizability*	**3.67**	3
	Integrate Technological Advances	**4.33**	3
	Multifunctionality	**4.33**	**3.67**
	Robust	**3.67**	**4.33**
	Universality	**1.66**	3
Material	Conserve Complexity	3	**3.67**
	Design for Separation	**<u>5</u>**	**3.67**
	Inherently Nonhazardous	**4.33**	**<u>1</u>**
	Minimize Material Diversity	**3.67**	**2.33**
	Renewable Rather than Depleting	**3.67**	3
Process	*Ease of Management*	**4.33**	**2.33**
	Facilitate Resource Recovery	**4.33**	**<u>5</u>**
	Integrate Material and Energy Flows	3	**<u>3</u>**
	Maximize Efficiency	3	**3.667**
	Output-pull versus Input-push	**3.67**	**4.33**
	Prevent instead of Treat	**4.33**	**4.33**
	Average Rating Overall	**3.75 ± 0.77**	**3.33 ± 0.94**

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	Flexible Sustainable Design	Fiber Shredder Design	Fiber Shredder Process	Design Rating Description	Process Rating Description
Design	**Durable** *Customizability*	**3.67**	**3**	Most of machine components do not suffer considerable wear and do not need to be often changed	Fibers created during the process increases the lifetime of textiles but has also a limited lifetime.
	Integrate Technological Advances	**4.33**	**3**	Most modules allow the addition/removal of components.	Process creates fibers that are shorter than new fibers, cannot replicate highest output quality yet
	Multifunctionalit y	**4.33**	**3.67**	Machine is composed by different modules that can be changed without interfering in other modules	Process generates material that can be used for multiple types of application but currently is only applicable to nonwovens
	Robust	**3.67**	**4.33**	Can successfully shred textiles into fiber but can only process small amounts of material	Is capable to meet the demand of textile waste achieving the capacity of recycling fiber and remove waste from the environment.
	Universality	**1.66**	**3**	Design is able to shred but not sort either input our output material	Can process most types of textiles but no other types of materials
Material	**Conserve Complexity**	**3**	**3.67**	Most materials can be repurposed or remanufactured, but some cannot.	Increases the life cycle of existing materials but creates new materials with limited life cycles
	Design for Separation	**5**	**3.67**	Materials can be easily disassembled, upgraded, and reassembled	Currently do not have a simple way to separate fibers, yarns, and pieces but a variety of textiles become more uniform in size
	Inherently Nonhazardous	**4.33**	**1**	Materials are not hazardous or harmful to the environment	Creates materials that can be hazardous and needs to be tracked such as microplastics

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	Minimize Material Diversity	**3.67**	**2.33**	Utilizes materials that are already embedded on bought components and materials to build the machine structure (Steel, Aluminum and Acrylic)	Utilizes various types of materials as inputs that cannot be processed together neither mixed. These materials require to be treated separately
	Renewable Rather than Depleting	**3.67**	**3**	Materials utilized are abundant in our planet but utilizes electrical energy from non-renewable sources	Utilizes materials available in waste, these materials are abundant but limited. Utilizes electrical energy from non-renewable sources
Process	*Ease of Management*	**4.33**	**2.33**	Machine can be easily opened for maintenance or changing components	Not able to sort and process different materials at the same time
	Facilitate Resource Recovery	**4.33**	**5**	Most materials selected can be directly sent to a recovery, recycling facility	Repurpose, recycle and remanufacture textiles successfully
	Integrate Material and Energy Flows	**3**	**3**	System can shred and movement material but need the assistance of other sources such as pneumatic and human	Utilizes existing material but relies on non-renewable sources of energy.
	Maximize Efficiency	**3**	**3.667**	Machine has an overbuild electronic system and could have improvements in energy usage	Utilizes waste to generate a product with value
	Output-pull versus Input-push	**3.67**	**4.33**	Fill the gap in the shredding technologies but not in an industrial scale	Process can satisfy the existing demand but are limited to materials that do not contain PFAS or other contaminants.
	Prevent instead of Treat	**4.33**	**4.33**	Materials utilized can be easily processed	The process can generate waste in the form of Dust (near 5%).
	Average Rating Overall	**3.75 ± 0.77**	**3.33 ± 0.94**		

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Table 6: Average results for different set of samples (n=3)

Set	W_{bc} (g)	W_{ac} (g)	W_{as} (g)	Textile Pieces (g)	Fibers and Yarns (g)	Dust (g)
A	23.08 ± 0.10	22.92 ± 0.14	22.09 ± 0.14	11.15 ± 1.45	10.94 ± 1.38	0.83 ± 0.00
B	22.85 ± 0.07	22.75 ± 0.00	21.85 ± 0.23	3.61 ± 0.80	18.23 ± 0.59	0.91 ± 0.01
C	22.97 ± 0.37	22.89 ± 0.36	21.94 ± 0.32	3.56 ± 0.80	18.39 ± 0.88	0.95 ± 0.00
D	23.24 ± 0.25	23.14 ± 0.21	22.03 ± 0.25	1.08 ± 0.74	20.95 ± 0.57	1.11 ± 0.00
E	23.21 ± 0.17	23.12 ± 0.14	21.80 ± 0.27	0.05 ± 0.07	21.75 ± 0.30	1.32 ± 0.01